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A STUDY OF 1.70 mm. GRAVEL MOVING AS BEDLOAD IN A LABORATORY FLUME

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "A STUDY OF 1.70 mm. GRAVEL MOVING AS BEDLOAD IN A LABORATORY FLUME" submitted by S. K. BHATTACHARYA in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The literature of bed-load transport is reviewed to ascertain the gaps in knowledge of behaviour in laboratory and field. Attention is given to correspondence between models and prototypes; simple experiments were devised to act as pilots for future work aimed at determining the limits at which correspondence ceases. A strong indication was obtained that, for a given gravel size, there is a lower discharge limit beneath which dunes will not persist. Some speculative formulas are suggested for test in future work.

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S. K. Bhattacharya.

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CHAPTER I

INTRODUCTION

1 - 1. Blench and Erb (Ref. - 1) have drawn attention to the gaps in experimental knowledge of sediment transport. A particular one that has come into prominence recently as a result of model studies using fine gravel is that the dunes to be expected from sand models do not form, or fail to persist if artificially formed, when discharge falls below some level. The importance of this peculiarity, if established, lies in the application to models as well as in fundamental understanding of sediment transport. River models usually concern sand-beds and use sand i.e. material whose settlement velocity varies with a higher power of sediment size than $\frac{1}{2}$, see fig. 1 (which shows settlement velocity against diameter for spheres of quartz in water at different temperatures); if a model concerns a gravel, sand is still likely to be used in the model because, inter alia, river gravel size in a model would be comparable with the depth of flow and obviously unrepresentative. However a large river can be modelled with its bed material scaled at least roughly according to the model's vertical scale and so that if the prototype bed material is large gravel the model material will still fall in the gravel range (which is roughly from 1.00 mm. up).

1 - 2. Obviously there are advantages in having a model whose bed materials obey the same settlement law as the prototype's; so sand is not the best material for modelling a gravel river even though it seems to reproduce qualitative behaviour well. However if the model gravel does not reproduce the bed behaviour of the prototypes it is just as objectionable as sand. Thus the question arises whether a large enough model, using gravel, would reproduce prototype behaviour and if so how large a model?

1 - 3. In tackling this problem the author soon found that literature contains remarkably little information of some kinds. Accordingly his research has been directed towards co ordinating material not only to obtain results from it but also to focus attention on the kind of work that has to be done to fill the gaps.

1 - 4. It would be appropriate at this stage to define terms and expressions used in the body of the text for various phases of bed-load movement and dune formations as follows: -

Antidunes. Dunes which migrate or move upstream.

Bed factor. V^2/d, denoted by F_b. (See App. B Symbols).

Bed factor zero. Bed factor when charge is vanishingly small. This is also termed "bed factor at vanishingly small charge" or "zero bed factor".

Bed-load. Solids moving along the bed by sliding, rolling, saltation, or a combination of these actions.

<u>Charge</u> The ratio of the weight per unit time of bed-load in a water sediment complex to the weight per unit time of the water.

<u>Dunes</u> Bed waves which move in the direction of flow and have their lengths large compared with their amplitudes (Fig 6).

<u>'Incipient' bed condition</u> The condition of bed at the commencement of motion or at the point of cessation of movement of bed particles.

<u>Gravel</u> In this thesis, quartz particles having diameters of 1.00 mm. and above.

<u>Relative bed factor excess</u> The ratio of difference of bed factor and bed factor zero to bed factor zero, i.e. $\dfrac{Fb - Fbo}{Fbo}$

<u>Ripples</u> Small bed undulations or small bed waves with lengths comparable to their amplitudes.

<u>Saltation</u> Bed movement by hops or by leaping.

<u>Sheet Flow</u> The condition of flow between a dune bed and an antidune bed when the dunes have been washed away and the bed is more or less a smooth one and all the particles are in motion. (Fig. 6).

CHAPTER II

THE BEHAVIOUR OF SAND BEDLOAD IN A LABORATORY FLUME

2 - 1. Descriptions of bedload transport and phases of bedload transport have been given by: Darwin (Ref. 2), Deacon (Ref. 3), Bagnold (Ref. 4), Schoklitsch (Ref. 23), Kramer (Ref. 6), Straub (Ref. 7), Gilbert (Ref. 8), Schields (Ref. 9), Inglis (Ref. 10), Ismail (Ref. 11), Simons and Richardson (Ref. 12 and 13), Tiffany and Bentzel (Ref. 14), Liu (Ref. 15), Danel, Durand and Condolois (ref. 16), Sundborg (Ref. 17), Lacey (Ref. 18).

2 - 2. The following descriptions have been compiled from them and the particular reference for each item of information is quoted.

(i) Ref. 2. "The ripple marks on a sandbed caused between two currents of fluid is dynamically unstable, but if a series of vortices be interpolated so as to form a function of the roller, as it were, it would be stable".

(ii) Ref. 3. Deacon states "The first movement of isolated sand particles was observed when the surface velocity reached 1.3' per second. The grains ranged themselves in bands perpendicular to the currents, resembling ripples on seashore .

Surface velocity V_s = 1.3' per second - ripples distinctly formed

V_s = 1.5' per second - ripples still more perfect moving at a velocity c = 0.0007' per second

V_s = 1.75' per second, c rose to 0.0016' per second

V_s = 2.10' per second c - rose to 0.042' per second

V_s = 2.125' per second - movement of ripples became irregular.

The sand particles which were rolled up the flat slope instead of toppling over the steep slope, were occasionally carried to the next crest.

V_s = 2.50' per second, sand grains clearing the top of first or second crests were carried further down stream.

V_s = 2.60 to 2.80' per second, ripples less and less well-defined.

V_s = 2.90' per second - ripples completely wiped away. The scour then became a completely different phenomenon, sand and water being mixed in a constant process of lifting, carrying and depositing. The average depth of scour and lift appeared nevertheless to depend on velocity."

(iii) Ref. 5, Leliavisky states that "Another approach to the same problem (formation of ripples and dunes) is outlined in Professor Richardson's 'Dynamics of Real Fluids' (London 1951). He points out that according to Bagnold's experiments (Ref. 4) the length of the characteristic sand ripples caused by the wind, is equal to the length of a jump of the "saltating" particles. Thus, both wave length of the ripple and the mean length of the jump of the sand grains are reduced when the size of the particles increases. The path of the particle in saltation zone is cycloidal and consists of a "succession of jumps". On the other hand, "under water, the ripples are more often produced by a laminar to - and - fro motion of the water relative to its bed".

(iv) Ref. 5 and 23. Leliavisky quotes from Schoklitsch's observation that "the vortex behind a dune had a horizontal axis and was capable of holding in position or slightly lifting the finer grains while the coarse particles fell down on slope. This is supposed to explain the sifting effects of dunes on bed materials".

(v) Ref. 6. Kramer observed "(a) Grain size and denseness have definite opposing effects on the critical tractive force of bedload mixtures. Therefore it is not justifiable to judge the movability of a bed of a mixture only by its grain size.

(b) For a given sand mixture the occurrence of excessive ripples varies directly with the slope.

(c) Well-graded coarse mixtures reduce the tendency towards excessive ripples.

(d) Based on requirements of laboratory technique well-graded sand mixtures are preferable for river models. Removal of finer components is sometimes advantageous.

(e) The commencement of the bed-load movement is at the lower critical range of tractive force".

"Correlation of critical velocity but of a somewhat different kind has also been deduced by Kramer from Gilbert's results. The first movement of sand (see fig. 2) and excessive ripple formation stands in certain correlation to the theoretical energy critical curve $V = \sqrt{gd}$ ".

(vi) Ref. 7. Straub states "At present, there is a definite gap between theoretical assumptions and actual occurrences. From a practical view point

this is unimportant provided the formulas theoretically derived give results corresponding to actual occurrences when suitable empirical coefficients are introduced. Thus the du. BOYS equation assumes that a series of thin laminae of sediment moves smoothly over one another over the entire streambed. As a matter of fact, observation reveals that except for unusual flow conditions, the sedimentary materials move downstream in ripples which roll over and over in a manner comparable to the movement of sand dunes. Just downstream of the miniature dune there is virtually no motion of sediment particles, such particles being rolled up the dune only to fall motionless at the downstream leeward side. This type of sediment movement is far different from that assumed in setting up the du Boy's theory. Nevertheless, for sediments with certain size limits (ranging possibly from something less than 1m.m. to about 4 or 5 m.m. in diameter) observations have shown that the equation gives satisfactory results with regard to the quantity of material moved provided satisfactory empirical coefficients are chosen".

(vii) Straub's observation showed "That the character of the ripple not only depended on the grain size and drag force but also on the kineticity of the flow. Experiments seem to show that the height and sharpness of the ripple approach a maximum when the flow in the channel is near the energy critical for higher velocities, the undulations are less rugged and for still greater velocities relative to the energy critical, the bed appears to become smoother, until finally the ripples disappear entirely leaving a smooth streambed. Experimental data available does not permit definite conclusions

concerning the relative influence of magnitude of tractive force and degree of kineticity of the character of ripple formation. Most experiments that have been performed by various investigators are either entirely for the streaming flow such as the author's or for shooting flow such as Gilberts. The writer's observations indicate that the length of the ripples is much less subject to fluctuation with flow conditions than the height. There is some indication that the ripple length increases with the water discharge when sediment load per unit width of channel remains constant. Straub further observes - "almost invariably the occurrence of ripples in the model is so greatly out of proportion to those which obtain in the prototype that the results of the studies have grave limitations in the applicability to the prediction of the results to be obtained from projects control measures". (Straub's sand was 0.7 mm. dia.)

(viii) Ref. 8. The classical experiments made by Gilbert not only fixed the starting point of bed movement but brought out two other critical stages in the process of movement: (a) transition from ordinary dunes progressing down stream to a completely smooth and washed out bed and (b) transition from this smooth bed to long rolling sand waves progressing upstream. i.e. 'antidunes'.

(ix) Ref. 5, Leliavsky says, Scheilds according to his experiments (Ref. 9) carried out in 1936 stated that "the controlling factors for bed undulations are (a) $\tau_c/\rho_1 D$ (b) D/δ' in which τ_c is the critical drag and ρ_1 is the submerged density ($\rho_s - \rho = \rho_1$), D is particle diameter and 'δ'' the well known parameter of turbulence theory."

(x) Ref. 10. Desai's experiments "with sand 0.21 mm, 0.43 mm, 0.65 mm. gravel 1.40 mm, 4.94 mm. in open channels and with materials of 4.22 mm. 8,70 mm. and 19.40 mm. in flumes showed that ripples do not form when the bed-material consists of gravel, but sand upto mean diameter 0.50 mm. produce ripples. Experiments with 'nala' sand 0.65 mm. showed that ripples do not form in 'nala sand' greater than 0.65 mm. and such small riplets as formed at higher stages of flow were due to an admixture of particles finer than 0.50 mm. Hence the presence or absence of ripples are closely linked with the way in which the particles move, which in turn depends upon the grade of material.

The height of ripples in unscreened white 'V' sand 0.24 mm. containing 5% of coarse materials above 0.6 mm. was only about half of that of ripples in screened 'V' sand of 0.21 mm. This difference was largely due to the coarse particles of unscreened sand accumulating in the troughs".

(xi) In the course of discussion Desai further observes "For a given length of ripple, the height is a maximum when the upstream and down-stream slopes are steepest. Bagnold (Ref. 4.) has pointed out "the length of the characteristic path of particles increases with increase in velocity". He was writing about air-transported sand, but the same holds for water transported sand; and as a result, the length of the ripple also increases with velocity, while the upstream slope flattens and deposition takes place at the crest so that the height increases. This is limited by the velocity at the crest; and increase in height relative to the increase in length decreases as the velocity at the crest increases,

until $\frac{l_r}{h_r}$ exceeds that for normal ripples, and dunes develop. Due to this flattening of the upstream slope of the sand dune, convergence of bed flows is reduced and is less than in the case of normal ripples and is insufficient to smooth out all the turbulences at the toe of the slope where flow emerges from the trough. This reduction of convergence leads to instability of flow and the formation of small ripples on the upstream slopes of the bed and each ripple having a roller with horizontal axis formed on its lee, as could be seen through a glass window in the side of the flume".

(xii) It was further reported that "when the water level was lowered rapidly, keeping the charge constant, vigorous scour occurred and the ripples which formed were higher and the final depth of water greater and the velocity lower than where water was lowered gradually, i.e. to say increased charge led to an increase of ripple height, an increase of depth and a reduction of velocity. It was further observed that with the same charge of 0.20 per ‰ (i.e. 20% ‰) but with various discharges of 3.0, 5.0 and 6.75 cusecs. small dunes formed on the bed and the height of dunes increased with increase in discharge, but the ratio of height of ripples to depth of flow were nearly similar".

(xiii) Desai further says "There are 4 distinct stages of bed roughness.

(i) Ripples (ii) a condition intermediate between ripples and dunes (iii) dunes (iv) sheet movement".

(ivx) The final conclusions are: -

"(a) Bed ripples and dunes are undulations which appear as a distinct pattern on the bed.

(b) The origin of ripple movement lies in the uneven movement of material caused by the flow of water.

(c) Random collections of particles occur on the bed. These create eddies and materials deposit at a point one ripple length downstream where the same process takes place and ripples appear on the bed further and further downstream as a series.

(d) Ripples develop wherever bed movement occurs even though it is very small and their shape and dimensions depend on the discharge of water, sand charge, the grade of material, its size distribution and specific gravity.

(e) With increase in bed movement ripples change to small, medium and large ripples and large ripples change to small, medium and large dunes, until eventually with still further increase in bed movement, sheet movement occurs.

(f) With increase in bed velocity the characteristic path of saltating particles increases and the ripple length increases with a corresponding small increase in height.

(g) The upstream slope of a ripple which has formed on a dune is dependent on the balance of forces between the rate of bed movement and the crest velocity. The downstream slope is determined by the angle of repose as controlled by the upward current of flow in the roller eddy (with horizontal axis) which forms in the trough.

(h) Bed ripples did not form on a bed of coarse sand.

(i) Ripple heights varied with different materials.

(j) The energy slope increased with coarseness of materials as well as with relative roughness".

(xv) Ref. 11. Ismail plotted ratio of velocities with and without ripples against depth and found that in case of rippled bed the maximum velocity was shifted higher than that for no rippled bed. Ripple formation in Ismail's investigation was a function of Reynold's number whereas in Deacon's case it was velocity and in Kramer's case it was tractive force.

(xvi) Ref. 13. Simons and Richardson found that the form of bed roughness from experiments carried out with a given bed material using a large recirculating flume 150' - 1" long, 8' - 0" wide and 2' - 0" deep could not be reproduced in a smaller recirculating flume 60' - 0" long, 2' - 0" wide and 3' - 0" deep. For example, the forms of bed roughness observed in the order of <u>increasing shear</u> in the smaller flume were:

(a) "Plane bed before beginning of motion. (b) Plane bed after beginning of motion. (c) Dunes (d) Transition from dunes to plane bed and standing waves. (e) Standing sinusoidal sand and water waves which were in phase. (f) Anti-dunes.

(xvii) Using the same bed material in the large flume the form of bed roughness in order of increasing shear were:

(g) Plane bed before beginning of motion (h) Ripples (i) Ripples superposed on dunes. (j) Dune (k) Transition from dunes to planebed and standing waves. (l) standing sinusoidal sand and water waves which were in phase. (m) Antidunes".

"The large flume produced the form of bed roughness observed in the field whereas the small flume did not. It was also noted that the height of dunes is related to the depth of sand bed. As the depth of bed material is decreased the amplitude of the dune increased.

(xviii) The form of bed roughness is related to the size and gradation of bed material. To illustrate using sand ranging from $D = 0.2$ mm. to 0.5 mm. it was observed that the amplitude of the dunes is independent of size of bed materials but the spacing and shape of dunes are related to size of bed material. The spacing of the dunes increases with decreasing size and the angle the fore plane of the dune makes with the horizontal decreases with decreasing size of bed materials. The net result is that resistance to flow is smaller with fine sand than with coarser sand by as much as 20%."

(xix) Ref. 12. Simons and Richardson experimented with 0.45 mm. sand and some of their observations were as follows: (Fig. 3, 4 and 5)

"<u>Tranquil Flow Regime</u>: - When d/δ' approached 0.53 movement of the material began and ripples started to form ($F_r = V/\sqrt{gd} = 0.15$). The total sediment load ranged from 1 ppm to 101 ppm. - - - - The bed changed from the ripple pattern to a dune pattern when the slope and/or depth were changed such that d/δ' was approximately 1.0 and the Froude number was approximately 0.28. The change was abrupt, and dunes established themselves all over the full length of the flume in a few hours. Velocities of dunes were from 0.02' to 0.70' per minute. The large dune velocities were associated with relatively steep slopes and shallow depths. With dune bed form of roughness, water surface was uneven and turbulent and water surface was

lower over troughs than over crests".

(xx) "<u>Transitions, dunes to standing waves</u>. - The change from dunes to standing waves was complex and the form of bed roughness was erratic. The transition occurred when the depth and/or slope were changed so that $d/\delta' > 2$ and $0.6 < F < 1.0$. With dunes the maximum Froude number was 0.60. Runs with a Froude number between 0.6 and 1.0 displayed a multiple roughness, that is, a bed form between dunes and standing waves which consisted of washed out dunes and sand bars. The change in roughness and consequently the change in resistance to flow and dissipation of energy were large when the bed changed from undulating form to dunes whereas the change in energy from a change in the Froude number was small when $Fr \approx 1$. Thus the velocity and depth were changed considerably when the bed form changed and small Froude numbers resulted. Conversely, the change from dunes to rapid flow resulted in smaller loss of energy because of the reduced roughness, which caused larger velocities, small depths and larger Froude number".

(xxi) "<u>Rapid Flow Regime</u>. - With rapid flow, $Fr > 1.0$, three forms of sand bed and water surfaces were observed: plane, standing waves and antidunes. Plane bed and plane water surface. - With fine sand as a bed material, plane bed runs are a common phenomenon, and they develop at $Fr < 1$ in the tranquil flow regime.

Standing waves. ---The standing waves formed when the Froude number was approximately 1.0; the undulating sand waves developed when $1.2 < Fr < 1.3$. Antidunes. - When the Froude number, which was computed on the basis of average velocity and average depth, was greater than 1.3 and d/δ' was greater than 3.0, antidunes formed".

(xxii) "For certain size gradations of bed materials, if the slope of the energy line is close to critical slope, a change in stage causes dunes to plane bed or standing waves and vice versa. This phenomenon occurs in many natural rivers and produces a discontinuity in the stage discharge relation. However, because of hysterisis that is associated with such a change in bed form, the stage at which discontinuity develops depends on whether the stage is rising or falling and on the rate of change of discharge with time."

(xxiii) Ref. 14.

Tiffany and Bentzel: observed "correspondence with the author has verified the fact that he used the largest grains as his criterion for movement assuming that, when they were in motion, all sizes up to the largest were also in motion. However the writers have found that for sands of mean grain size smaller than 0.5 mm. the large grains moved first and that if their movements were used as a measure for general movement an erroneous value of critical tractive force would be obtained. This curious phenomenon has been noted independently by other observers".

(xxiv) Ref. 15. Liu concludes "Through the review of existing literature and combination of interfacial instability of stratified flow with flow over an alluvial bed, sediment ripples are explained as caused by the instability of the interface, which is a transition layer between the fluid and the bed. Such a transition layer can be in three forms: (a) Laminar boundary layer (b) Laminar sub-layer or vortex layer". He also found that other factors "such as turbulence, surface waves,

small irregularities of the bed are not primary cause of the sediment ripple formation although they may affect movement of sediment ripples".

(xxv) Ref. 18. Lacey states "Danel, Durand and Condalois (Ref. 16) concluded that saltation is the dominant action in bed load movement" and that "it occurs within a well defined zone which they term as "saltation layer". For this purpose the grains must be large enough to be independent of each other or "incoherent".

They also conclude that saltation which plays an important role in the behaviour of rivers with a mobile bed "Influences the bed configuration and helps to determine the cross section and slope".

(xxvi) Ref. 18. Lacey states that "Finally it is appropriate to quote the opinion of Sundborg (Ref. 17) that "there are no definite modes of intermediate between ripples and bars and that an even surface is an unstable transport form . . . . . the only stable surface is a rippled one when the flow is smooth and transitional".

(xxvii) Ref. 18. Lacey concludes "There is a well marked range for sediment transport by saltation. (i) The lower limit is that of fineness in the particles sufficient to cause cohesion, the range itself is marked by random ripples and (ii) The upper limit is that when ripples are replaced by well marked bed waves. It is to this last mode of transport involving bed waves that Blench's research has been directed".

CHAPTER III

THE BEHAVIOUR OF SAND BED LOAD IN A RIVER OR CANAL

3-1. Descriptions of bedload behaviour in rivers and canals have to depend largely on the modern technique of sonic sounding although the existence of dunes on canal beds after a canal has been closed has probably been known for centuries. The references found were Blench - Ref. 10 and Carey and Keller Ref. 20.

3-2. Ref. 19. The observations of Blench on Fraser (tidal) river bed - movement are as follows: -

"(i) Marked change of river cross-sectional form, at a section, starts and ends at approximately the same high stage.

(ii) Bed waves and dunes are always present.

(iii) During changes of cross-sectional form, bed waves increase enormously in length, height and speed up to 500' long, about 15' high and 250' per day.

(iv) There is a distinct, direct relation between bed wave length and stage.

(v) Scour produces a coarsening of bed materials.

(vi) There is a rough, but distinct correlation between grain size of bed material and depth of flow at a section."

3-3. Blench further states: -

"While the Hope discharge remained below 350,000 cusecs. with low-low tide up-till June 15th, the waves were of the order of 20' long and a

couple of feet high; where a few of them formed distinguishable groups, the group speeds were of the order of 20 to 50 feet a day. When 350,000 cusecs was exceeded the waves became conspicuously larger. As river stage increased so did the wave size. In particular, on the 23rd, in range 20 - 22 a specially large wave that had started to grow on the 20th, attained a full size of about 500 feet long and 15' from trough to crest, and maintained a fairly, steady rate of progression of about 250' per day till about 29th ... by that time the Hope discharge was back to a little under 350,000 cusecs and the low-low tide was a little lower than on the day when bed activity started. i.e. June 15th ... on the 29th this wave developed corrugations on its back and on the 30th it lost its identity and was replaced by a train of small waves such as existed before the 15th. (Fig 7 & 8)

3 - 4. Ref. - 20, Carey and Keller concluded from a study of the bed movement of Mississipi river"(1) That sand waves exist generally on the river bed in a systematic manner (2) that the sand waves tend to vary in amplitude and spacing with variations in discharge (i.e wave tend to become larger with increases in discharge and smaller with decreases in discharge) (3) That a major source of resistance to flow in an alluvial river, is provided by a primary system of sand waves which in its turn is created by the river itself and operates as a means of controlling its orderly progression down its valley. (4) That the waves constitute a major component of resistance to flow has not been confirmed, although it still appears reasonable."

3 - 5. They also state that "There is a lag in the rate of change of sand waves and on a continuously rising river, the waves are somewhat smaller "than they should be" and on a falling river," they are somewhat larger than they should be". The fact that the rating curve at any given station is a "loop" rather than a curve may be partially explained on the basis of a lag in sand wave adjustment,that is the smaller waves present on a rising phase offer less resistance to flow and the larger waves present on a falling phase offer more resistance to flow."
(Fig 9- 12)

3 - 6. The following interesting observations and arguments are reproduced from Kramer's Paper. (Ref. 6)
"Lower limit for commencement and cessation of movement: ----numerous observations were made during falling stages to determine the point at which bed load movement ceased. The general result of the comparable observations is that the tractive force at which movement stops is 0 to 20% (on the average 12%) larger than at which it begins. On the other hand, observations in nature conducted by Krapf (Ref. 21) and by Kreuter (Ref. 22) show that tractive force was measured to be 20% greater at the commencement of "geschiebe" movement than at its cessation, while Schoklitsch's experiments (Ref. 23) with unigranular sand showed "that this difference depends on the finer constituents of the sand and that for clean uniform sand, the difference approaches zero".

3 - 7. " - - - - - - This apparent contradiction is explained as follows - At equal depths and slopes and therefore at equal tractive forces, the relative roughness determines the rate of flow and the impulse of a given mass of water. With the movement in progress, the frictional resistance to movement is always less than that required to overcome frictional resistance at rest, therefore considering impulse of a given mass of water.

$$I_o \text{ (beginning) } > I_o \text{ (end) or}$$

$$d_o u_o > d_o' u_o'$$ Thus the conclusions of Krapf and Kreuter are justified under assumptions that, for like stages of movement, equal velocities existed at equal depths and slopes.

3 - 8. In the present experiments, the commencement of movement occurred in an artificially prepared smooth bed. For the observations made after cessation of movement, the bottom surface had been disturbed by natural forces, resulting either in ripples or in the rearrangement or sorting of the particles. This difference in roughness resulted in the fact that, for same depth of water the slope being held constant the water would flow through the flume at a lesser velocity during the falling stages than during the rising stages. This difference amounted to 0 - 25% (14% on average). A simple computation shows that in comparable observations of these experiments, the impulse was less at the cessation of bed-load movement than at its start and amounted to (100% - 14%) x (100% + 12%) = 96% of the starting impulse".

3 - 9. Ref. 24. Vanoni says "smaller friction factor of the rising flood can be explained by a difference in bed configuration between the river on rising and falling stages. Simons and Richardson contest the above and are inclined to explain this difference by a time lag in the change of bed forms.

Chou states that velocities are higher on rising than on falling stages of a stream because the slope is higher during the rising stages than in the falling stages. Messrs. Laursen and Chou have advanced the idea that resistance to flow offered by grains in the bed is different when they are moving than when they are fixed and suggested this may account for the lowering of the resistance observed for sediment laden flows".

3 - 10. The Poona experiments showed that with the same concentration (Ref. 10) of charge, the heights of dunes increased with increase in discharge, but the ratio of heights of ripples to depth of flow were nearly similar. These observations in the model agree with the observations of Blench (Ref. 19) and those of Carey and Keller (Ref. 20) on Mississipi River, "that the waves tend to become larger with increase in discharge and smaller with decrease in discharge".

CHAPTER IV

THE BEHAVIOUR OF GRAVEL BED-LOAD IN A FLUME

4 - 1. The following references 10 and 25 describe gravel behaviour in a flume or in a model.

(i) Ref. 10. Experiments carried out in open channels at the Poona Research Institute with sand of 0.21 mm., 0.25 mm., 0.43 mm., and 0.65 mm., and with gravel 1.40 mm., and 4.94 mm., 4.22 mm., 8.70 mm., and 19.4 mm. in flumes showed that ripples do not form where the bed material consists of gravel but that sands up to about 0.5 mm. mean diameter produce ripples.

(ii) Ref. 25. Durand while making experiments in pipes with sand and gravel mixtures observed - "Fine sand is transported by suspension and gravel by saltation. The transportation of uniform grains which exceed 0.15 mm. leans to be in pure suspension. Transportation by pure saltation starts when the grain size exceeds 2.0 mm. It is remarkable that critical dimensions coincide with those which separate the fields of application of the limit settling velocity laws of isolated grains in calm water. Particles up to 0.15 mm. follows Stoke's law. Above 1.50 mm. the relative movement of grains is entirely turbulent and follows Rittinger's law. This coincidence between the laws of settling velocity as a function of nominal diam. in calm water leads one to think that in matters of hydraulic transportation the value of average slip velocity of the particles related to the liquid remain almost the same as that of settling velocity. A similar assumption has already been made in

Schmidt-Rouse theory of transportation by suspension. He further states that in the turbulent movement the drag coefficient C_d - is constant and so in a pure saltation regime the relative movement of grains would be independent of the liquids viscosity value and hence of the flows' degrees of turbulence".

4 - 2. The available data for gravel in the streaming flow conditions are rather meagre but from the above it appears that gravel in laboratory flumes can behave differently from sand in the following respects:-

(1) Gravel-beds do not form ripples but they form dunes if sufficient charge is available.

(2) The difference in the behaviour of gravel seems to occur at small charge.

(3) Gravel behaves like sand from the dune phase onwards.

CHAPTER V

THE BEHAVIOUR OF GRAVEL BED-LOAD IN A RIVER OR CANAL

5 - 1. In a recent statement Blench has said that sonic sounders record all saltating stones in a gravel river when transport is appreciable, so do not give useful readings.

5 - 2. (Ref. 27.) The following description of canals in San Luis Valley has been compiled from Lane's paper "Some Factors Affecting the Stability of Canals Constructed in Coarse Granular Materials". The San Luis Valley is 80 miles long and 40 miles wide. The bottom is saucer shaped, slope near the sides of the valley is 30' per mile - but they flatten downwards. Deposits have formed a bed cone shape, angle in between is 90° and slope of 15' per mile near apex of cone - the subsoil consists of sand, gravel and cobbles, the size of cobbles decreasing with distance from apex. They cover a wide range of conditions of discharge, slope and bed materials (0.20" to 3.20" diam. size). Lane concludes "The force necessary to cause movement of non-cohesive material on a sloping side of channel is less than that required to cause motion of the same material on a level bed. The ratio of the force necessary to cause impending motion on a sloping side to that required on a level bed is shown to be a function of slope of the side and angle of repose of the material".

Gravel bed load data of a river or canal was not available. However, it may be stated that a river with gravel bed differs

materially from a sand-bed river in as much as gravel rivers show an unsystematic mechanical analysis of particles distribution on their bed while mechanical analysis of river sands show a definite pattern.

5 - 3. The following are reproduced from the observation of Blench from his Fraser River studies: "Bed sediment analysis" (Ref. 28).

"(i) The first major result is that the bed-sand sizes during low-low and high-high tides do not appear to differ significantly.

(ii) The second major result is that there is a fair correlation between median grain size and depth at a point in any one river branch. (See Fig. 28)

(iii) The third major result is that when sand size is plotted against time the only point that suggests a correlation between size and river stage through time is A_3. If we accept the evidence of 7 points against one, it appears stage does not affect bed sand size unless scour results".

5 - 4. While the mechanical analysis of river sand from the different regions of dune crest, downstream slope and trough follows a systematic pattern, that of gravel does not. This is possibly due to the fact that the settlement velocity of particles of gravel range follow the $\frac{1}{2}$ power law so that the bed velocities required to move particles of different sizes would have to be more widely different than for sand particle sizes of comparable range.

CHAPTER VI

ANALYSIS OF BED-LOAD TRANSPORT DATA

6 - 1. Methods of analysing quantitative information on bedload transport vary among themselves, and the data themselves are often difficult to understand, because conditions of experiment (e.g. the addition of load of which portion goes in to suspension) are often indeterminate and the measurements somewhat vague. Nevertheless the total information analysed consistently may be expected to average out variations so as to show changes of phase by some change in plotted results; of course there may also be change of phase without obvious change in plotted results.

6 - 2. Plots of various types have been made by:
Blench and Erb - figs. 13, 14, 15 & 16, Einstein - fig. 17 & 18,
Meyer-Peter - fig. 19, 20 and 21.
Inglis - fig. 22, Simons & Richardson - figs. 3, 4 & 5.
Albertson, Simons and Richardson - fig. 23, Sheilds fig. 24.
Liu - fig. 25, Culbertson - fig. 26, H. Rottner - fig. 27. They are discussed in paragraphs 6 - 4 to 6 - 19.

6 - 3. For definitions, definition sketch and symbols refer to P. 2,3 P. 75 and pp. 68,69 respectively.

6 - 4. Figure 13 shows a plot of [illegible] against "charge" for Gilbert Sand ranges A to H.

The Gilbert sands were more or less of uniform diameter and most of the readings are for shooting flow conditions with a few in streaming flow regimes. The bed factors zero of the Figure were estimated, for lack of data, from Fbo = 1.9 Dm . This plot does not show either the commencement of ripple or dune regimes but show that with the change of phase from dune to sheet flow there is a discontinuity in the region of bed factor = 32.20.

6 - 5. Fig. 14 shows a plot of V^2/gds against $Vb/N = \nu$ and gives the lines for different concentrations from zero to 500% per No. This graph is presented to co-ordinate Gilbert-Murphy and canal data and has an equation of the form:

$$\frac{V^2}{gds} = \left(\frac{Vb}{\nu}\right)^{\frac{1}{4}} \left(\frac{1}{1 + ac}\right) = 3.63$$ a constant; for the factor 'a' Blench found a value of 1/400 for Gilbert uniform sand and assumes a value of 1/233 for graded mixtures.

6 - 6. Fig. 15 shows a plot of charge, C, against relative bed factor excess $\frac{Fb - Fbo}{Fbo}$. The plots are from Gilbert, Straub, and U.S.W.E.S. No. 17. This graph gives interesting readings. Though Blench adopted a linear equation of the form $Fb = Fbo\ (1 + aC)$, for practice the lines underneath give the equation $Fb = Fbo\ (1 + aC^n)$. An examination of the lines gives values of n = 5/6 for A, B, C & D sands of Gilberts, for U.S.W.E.S. no. 17 Sands 3, 7 and 8, and for Straubs' sand No. 6 as shown in the plot. All these sands have median diam. ranging from 0.2 mm. to 0.787 mm. Gilberts' sand No. E has a

particle size of 1.765 mm. and the value of 'n' for this sand is 0.77 or 9/12 approximately. The value of 'n' for F, G, H sands is $\frac{1}{2}$. The settling velocities of particles in calm water of size ranges 0.2 mm. to 0.5 mm. vary approximately as their diam. i.e. $V_s \propto D$; those in the size ranges between 1 mm. and 2 mm. vary as $D^{\frac{3}{4}}$ to $D^{\frac{1}{2}}$ and those in the size range above 2 mm. vary as $D^{\frac{1}{2}}$. The correspondence between the indices of 'C' and those of D for settlement velocity in calm water is striking.

6 - 7. Fig. 17 & 18 give a semi-log plot of Einstein's versus (Ref. 29) for gravels of sizes from 28.6 mm. to 0.315 mm. and sands 0.17 to 3.7 mm. where

$$\phi = \frac{1}{F} \cdot \frac{q_s}{(\rho_s - \rho_f) g} \cdot \sqrt{\frac{\rho_f}{\rho_s - \rho_f}} \cdot \frac{1}{g^{0.5} D^{1.5}} \quad \text{and} \quad \psi = \frac{\rho_s - \rho_f}{\rho_f} \cdot \frac{D}{S.R}$$

$$F = \sqrt{\frac{2}{3} + \frac{36 \mu^2}{g D^3 \rho_f (\rho_s - \rho_f)}} - \sqrt{\frac{36 \mu^2}{g D^3 \rho_f (\rho_s - \rho_f)}} \quad \text{where } \mu = \rho_f \nu$$

and D = diam. of the particles μ = absolute viscosity

ρ_s = density of solids ρ_f = density of the fluid

ν = kinematic viscosity

q_s = weight of the transported quantity of bed-load per unit width of bed per second (specific bed load transport) weighed dry.

(All in C.g.s. units - the above formula for F is that of Rubey (Ref. 26)).

From Fig. 17 for uniform grains it will be seen that for all points with values of less than 0.4 a straight line fits with the equation

$$0.465 \phi = e^{-0.391 \psi}$$

Einstein's Fig 17 fits the whole data with a gradual curve (1), though fitting by means of two straight lines, the second shown dotted by the writer, would seem to be more consistent with plotted points, suggesting of course a discontinuity of flow conditions. A further close examination reveals that the points lower down the curve are for material having diameter less than 1.00 mm. The equation of the dotted line will also be $\phi = e^{-k_2 \psi}$ where values of, k_1 and k_2 will be different from 0.465 and -0.391.

6 - 8. No general conclusion seems possible from the plotted points of in fig. 18 for sand mixtures, which suggests that the parameters are not suitable by themselves for sand mixtures.

6 - 9. Fig. 19 shows Meyer-Peter's plot of $q_s^{2/3} J/d$ against $g_s^{2/3}/d$ for gravels of 28.60 and 5.05 mm. Zurich Laboratory and 7.02 mm. 4.94 mm. and 3.17 mm. Gilbert sands. (Ref. 30)

The equation of the curve is $\frac{q_s^{2/3} J}{d} = 17.0 + 0.4\, g_s^{2/3}/d$

Where q_s = discharge quantity determining the bed load transport per unit width of bed per second(specific discharge quantity)

g_s = weight of the transported quantity of bed-load per unit width of bed per second weighed dry (specific bed-load transport)

d = diameter of the particles of the bed load material determined by a squared sieve.

"a" and "b" are constants. For the beginning of the moving of the particles g_s = o and the equation reduces to $\frac{q_s^{2/3} J}{d} = a$ For q_s - in kg/m per sec d - in meter and g_s in kg/m per second; a = 17, b - 0.4.

6 - 10. Fig. 20 gives a plot of 5.05 mm. particles of natural gravel $\gamma_s'' = 1.68$, Lignite breeze $\gamma_s'' = 0.25$ and Baryta $\gamma_s'' = 3.22$

Fig. 21 gives the plot of $q_s^{2/3} J/dm$ against $q_s''^{2/3}/dm$ for uniform grain and sand mixtures where dm = median (d 50) dia

q_s'' = specific bed-load weighed under water

γ_s'' = specific gravity of particles in water

$= (\gamma_s - \gamma_w)$

The Meyer-Peter plot does not show any discontinuity due to change in phases of bed.

6 - 11. Fig. 22 shows Inglis' plot (Ref. 10) of $V^2/gd \cdot \left(\frac{\rho}{\sigma - \rho}\right)$ against $\frac{D}{d}$ for gravels of diam. 4.00 mm. to 12.00 mm. median diam. and of sp. gr. 2.90 and for cubical to isolated Blocks of sp. gr. 3.61 to 2.14 - the sides ranging from 12.00 mm. to 24.00 mm.

The conditions are that the particles or blocks are just in the beginning of motion.

This plot gives the equation for gravel

$$\frac{D}{d} = 0.34 \left(\frac{V^2}{gd} \cdot \frac{\rho}{\sigma - \rho} \right)^{1.3}$$

He further states that when $\frac{V^2}{gd}$ in river = $\frac{V^2}{gd}$ in model and sp. gr. of blocks or stones in model and prototype are equal stones above $\frac{1}{4}$" grade in a channel less than 1' - 0" deep behaved similarly under conditions of equal $\frac{V^2}{gd}$ with diameter $\propto$ depth; but pebbles less than $\frac{1}{4}$" grade tended to depart from this relationship. The same was true of cubical blocks of various sizes ranging from $\frac{1}{2}$" to 2" cube. In other words, with equal F (= $\frac{V^2}{gd}$) in model and river, blocks and stones behave similarly when $\frac{\text{median dia. of stone}}{\text{depth of flow}}$ is the same for model and river within the limits stated.

When the Froude number of the prototype is not equal to the Froude number of model but stones and blocks have same specific gravity, experiments showed that $\left(\frac{D}{d}\right) \quad \left(\frac{V^2}{gd}\right)^{1.3}$ approximately at commencement of motion. Thus if ratio of Froude number (Model: River) is 1.2, the grade of the stone in the model should be increased in the ratio: -

$(1.2)^{1.3 \times 3}$ = 2.04 above that given by the depth scale.

6 - 12. Fig. 3, Simons and Richardson from their experimental results with 0.45 mm. sand and charge varying from 0.1% to 1510 % per %o plotted velocity against depth and defined the various bed-characteristics of plane, ripple, dune, transition, standing wave and anti-dune beds by plotting the appropriate lines for different values of Froude numbers on the curve.

Their results are:

Formation of ripples at Fr = 0.15, bed factor = 0.725, charge = 0.10% %o

Formation of dunes at Fr = 0.28, bed factor = 2.52, charge = 10.0% %o

Formation of transition at Fr = 0.60, bed factor = 11.65, charge = 100.0% %o

Formation of standing wave at Fr = 1.00, bed factor = 32.2, charge = 200.0% %o

Formation of antidunes at Fr = 1.30, bed factor = 54.5, charge = 800.0% %o

Their plots (fig. 4) of charge against tractive force defined the different phases of bed and showed discontinuity at Froude Nos. 0.60 to 1.0 or bed factors 11.95 to 32.2 with charge varying from 100 to 200% per %o, for the dune to the transition phase and from the transition to standing wave phases. Their plot $\frac{V_* d}{\nu}$ against $\frac{V}{V_*}$ $\frac{T_o}{4 \gamma_s d}$, Fig. 5, also defines the various phases but the discontinuity in flow is not marked in this plot

6 - 13. Fig 23, Liu (Ref. 31) gives Albertson, Simons and Richardson's proposed plot of $\frac{U_*}{w}$ against $\frac{wd}{\nu}$ which defines ripple, dune, transition phases by different curves showing each phase has a distinct pattern. Sheilds curve Fig. 24 for beginning of motion and Liu's curve Fig. 25 for ripple formation are also plotted in fig. 23 and the necessary comparison can now be made.

6 - 14. Fig. 26 shows Culbertson's plot of velocity against hydraulic radius which indicates Lower regimes (Dunes) to follow a straight line law and upper regime (flat bed, standing wave, antidunes,) to follow another parallel curve. Culbertson in course of discussion observes "Moreover the relationship between bed configuration and mean velocity of flow appears to be related to the phenomena of stage discharge discontinuities which exhibit themselves in true alluvial channels.

6 - 15. Fig. 27, C. Blanchet observes "In this connection we would like to draw attention to an article by M. Kottner in "La Houille Blanche" June 1959. M. Kottner collected 2500 experimental results and succeeded in classifying them in terms of the following parameters: -

$$d/D, \quad \sqrt{\frac{S}{\sqrt{\frac{\gamma_s-\gamma}{\gamma}}}}, \quad \frac{V}{\sqrt{h}\sqrt{\frac{\gamma_s-\gamma}{\gamma}}}, \quad \sqrt[3]{\frac{G}{\sqrt{\frac{\gamma_s-\gamma}{\gamma}}\cdot\gamma_s\cdot\sqrt{h^3}}}$$

in which G is the sediment load, D = depth of flow, d = the 50% grain size of bed material, S = slope, z = distance from the boundary, h = the value of z at centre of channel. The special features of the graph $\frac{V}{\sqrt{\frac{\rho'-\rho}{\rho}}\sqrt{gh}}$ against $\sqrt[3]{\frac{G}{\rho'\sqrt{\frac{\rho'-\rho}{\rho}}\cdot\sqrt{gh^3}}}$ are noteworthy. - Vide fig. 27.

6 - 16. It is particularly noteworthy that the number of points that the plot shows in the bed load charge range C = o - 40% per %o is remarkably small, though this is the range in which most engineering problems lie; the data for ranges of gravel is particularly meagre.

6 - 17. An outstanding feature of plots by Blench, Simons and Richardson and Culbertson Fig. 13, 4 & 26 is that they show a discontinuity or transition of law from dunes to sheet flow but not from ripples to dunes or sheet flow to antidunes. On the otherhand, Einstein and Meyer-Peter, figs. 17 to 21, show no such change by their fitting curves, but the data of Einstein, Fig. 17, at least do seem to show the need for fitting by two curves.

6 - 18. All the plots of $\underline{U_*}$ against $\frac{u_* d}{\nu}$ however show different laws for different regimes of initial movement, ripple, dune and transition, (figs. 23, 24 and 25).

6 - 19. No available data are adequate to show whether there is some peculiarity about gravels at small charges and small discharges. Accordingly the author decided to use the admittedly limited flume apparatus that is available in the laboratory pending construction of the new equipment to see if "small-charge, small-discharge behaviour" could be analysed to show results of increasing discharge. The experiments are described below. Their analysis indicated that, as discharge increases, small charge conditions tend to what would be expected from sand behaviour or from plots such as those made by Blench and Erb from the Gilbert data by assuming "Zero Bed Factors" derived from field observations of sand bearing canals.

CHAPTER VII

E X P E R I M E N T S

7 - 1. The experiments are described under the sub-heads

(i) Apparatus

(ii) Procedure

(iii) Detailed observations

The results are given in Tables 1, 2, 3, 4 & 5. Appendix A.

(i) Apparatus

7 - 2 The apparatus consisted of the following: -

(a) Adjustible glass walled flume

(b) Entrance tank to flume

(c) Exit tank from flume

(d) Pitot tube

(e) Manometer

(f) Current meter

(g) Charge injecting apparatus

(h) Orifice meter

(i) Scales, gauges, tapes, trays, etc.

7 - 3 Adjustible glass walled flume: The flume consisted of a 12" wide, 2'-6" deep and 18' - 0" long rectangular channel with glass sides and brass bottom. (Fig - 30) At the upstream end at 2' - 0" from the

entrance it had a vertically sliding gate worked by means of a rack and pinion arrangement which could shut off the flow completely or allow undershot flow or free flow as desired.

7 - 4. The flume was mounted on a frame work of channels, rolled joists and angles. This frame is supported at the upstream side on a steel stanchion 3' - 6" high and on the downstream end it is supported by a screwjack having a pipe at the top. The channel frame work of the flume is supported on the two ends of this pipe by means of flats bolted to the web of channel. Two half inch diameter steel rods with rounded shoes are attached on either end of the frame to make it stable.

7 - 5. The inlet tank is rectangular in cross section: 3' x 4' x 6' high with a curved approach to the flume. The inlet pipe was of aluminum -8" outside diameter and was fitted so as to discharge at the bottom of the tank vertically downwards. The eddies and turbulence created were damped by means of two vertical baffles - one a wooden perforated plate fitted vertically about 1'0" behind a steel baffle wall fixed at the entrance to the flume.

7 - 6. The outlet consisted of a steel tank 2' -3" x 1'2" x 2'3" fitted to the flume by means of a steel framing. The exit from the outlet tank was through a vertical pipe 6" in diam. which was provided with a plate valve worked vertically up and down by means of a spindle. A second sump about 9" from the end had a triangular shape in longitudinal view and was 2'-0" long at top at the floor level and 18" deep. This

sump was fitted with a 4" diam. pipe towards the bottom and could discharge from either end .

7.- 7. The pitot tube was fixed on the top of the flume on movable angle rails. The scales were fixed on a triangular movable frame having a ratio of 1 vertical to 3 on the hypotenuse. This gave a magnification of 3 in the scales along the hypotenuse and the scales were graduated accordingly.

7.- 8. A manometer to read the longitudinal slopes was erected. This had tubes fitted to the bottom of the flume along the central line at three points, a, b & c, the distance a-b being 75" and b-c - 60". The point 'a' was at the upstream end 2'-0" from the entrance and point 'c' was 48" above the outlet end. The ends of the three tubes were open to the atmosphere and the scales were fixed on the vertical.

7.- 9. The current meter was of the propeller type. There were 4 sizes No. 10672 - 4, 1, 2, and 2-2. The constants of the propeller: No. 2-2 which were used for velocity measurements were as follows: -

$$V = 0.2817\, n + 0.407 \text{ for } n < 1.97$$

$$V = 0.3283\, n + 0.315 \text{ for } n > 1.97 \text{ but } < 5.31$$

$$V = 0.3493\, n + 0.203 \text{ for } n > 5.31$$

Where V = velocity in feet per second and n = number of revolutions per second

7. - 10. The sand injecting apparatus consisted of a tray fed from a wooden hopper. The tray was mounted on a steel frame and was given to and fro motion by means of a connecting rod and crank arrangement.

The length of the connecting rod could be adjusted by fixing it at different positions of the slot. This gave a wide range of calibration from 1.0 gms/second to about 12.0 gms/second. The apparatus was calibrated for 4 ranges between 1 gm. per sec. to 5 gms. per second about.

7 - 11. The orifice meter could read discharges accurately from 0.2 cusecs. to 1.6 cusecs. The meter was fitted to the pipe in between flange couplings. The readings of the meter were automatically recorded on a graph paper mounted on a clockwork which gave discharges against time. The constant of the meter was 1.60.

7 - 12. Several scales were erected on the sides of the flume to read depth of sand, water, water surface, profiles, sand wave profiles, etc.

7 - 13. <u>PROCEDURE</u>: The flume was filled with 1.70 mm. median diam. sand to a depth of about 3½" and the surface of the sand was levelled off. The sand used in the flume was sieved by means of a mechanical shaker with sieves Nos. 4, 8 and 16; those passing through No. 8 and retained on No. 16 were taken.

A semi-logarithmic plot of a sand sample taken before the experiment is shown in fig. 31 and that of samples taken from the bed of the flume after experiment is shown in fig. 32. From these figures it is seen that the median diameter of sand was 1.70 mm. before the commencement of the experiment and 1.73 mm. after the experiment.

7 - 14. It was decided to run the flume (a) without charge and (b) with charge and observe the bed characteristics. For this purpose 11 runs were made without charge with discharges from 1.246 cusecs to

0.32 cusecs, with depths ranging from 1½" to about 2.0" and 12 runs with charges ranging from 5.6% per [illegible] to 63% per [illegible] for discharges varying from 0.256 to 0.384 cusecs. These runs were made for sufficient time to allow them to develop a working regime condition; the times were between 6 hours to 60 hours. For runs Nos. 1 - 11 the working regime was supposed to have been established when the particles composing the bed were just on the point of starting or stopping. For runs No. 12 to 23, the condition of bed activity was supposed to have reached a working regime when the movement of the grains as evidenced by formation of dunes, or plane bed movement, appeared to be on the average the same for a period say over 5 to 10 minutes.

7 - 15. The following were recorded - (a) Depth (b) Discharge (c) Slope (d) Rate of progression of dunes (e) Dune length (f) Dune height - the last three (d) (e) and (f) in some cases only. Results are in Tables No. 1, 2, 3, 4 and 5.

7 - 16. Measurements of Depths: Depth measurements were taken from the scales erected on the two sides of the flume. The observed mean value fairly agreed with the mean depth obtained from profile measurements. The method of measurement of depths at the sides were therefore adopted. In a recent comment on measurements of depth in a mobile bed flume Blench states " - - - the mean of the mean depths observed on each side of the test reach differed by a very small but statistically significant amount from the mean found from that mean and the mean depth along the centre line in the small flume. Also the mean depths taken from the sides by

planimetering the bed wave profiles did not differ significantly on an average from that given by averaging the two extreme depths of each of the planimetered profiles - perhaps the mean bed elevation might quite accurately be found by smoothing out the dunes after a run".

7 - 17. In certain cases in addition to the measurements at the sides, measurements in the centre were also taken by a point gauge and the mean found out.

7 - 18. Discharge: The discharge was measured by means of the orifice meter and was checked by measuring the velocity by a pitot tube and a current meter. The readings of the meter were more close to the pitot tube than those of the current meter. The discharge therefore was recorded from the orifice meter and no mean velocity measurements were taken.

7 - 19. Slope: The flume was about 18' - 0" long. Attempts to measure the slope of the water surface by means of a water manometer were not satisfactory. However some slopes were recorded but these cannot be accepted as correct due to effect of the exit and entrance conditions.

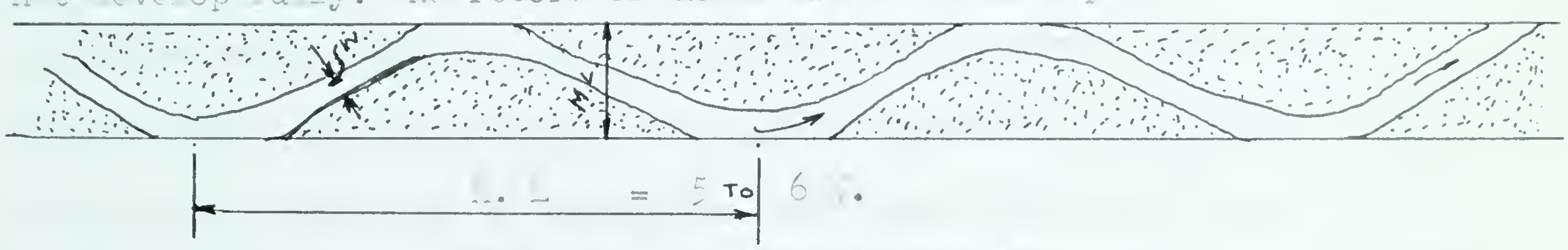
7 - 20. Rate of Progression of Dunes: The average speed of the dune was measured by measuring the distance a dune travelled and noting the time. For this purpose a distance was marked on the side of the flume and the time (by means of an electric stop watch) the dune head took to cover the distance, was recorded.

At the end of the run the details of the dune heights and lengths were measured.

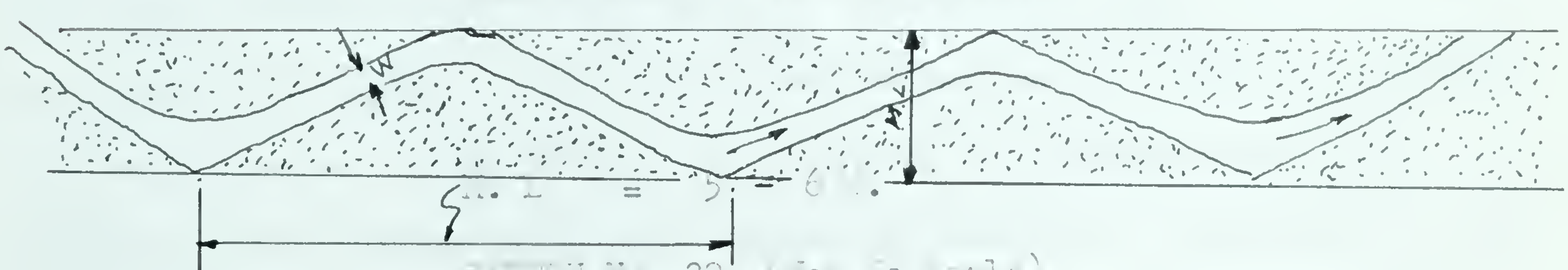
7 - 21. In run 3 the dune profile was sketched on the side of the glass flume and has been reproduced in fig. 33.
The photographs fig. no. 34 - 37 give an idea of the shape of the dunes which developed.

7 - 22. Details of observation of bed characteristics are given against each run as follows: -

7 - 23. <u>Detailed observations:</u>
Trial runs: Two trial runs were made with the flume bed nearly horizontal. In the course of these two runs, it was observed that if the discharge is shut off quickly, the bed develops a meander pattern - but due to insufficient width, the development was still incomplete. The two distinct meander patterns developed are shown in figures 38 and 39. The meander length in each case was about 5 to 6 times the width of the stream 'W'. From sketches 38 and 39, it is seen that the meander could not develop fully. No record of these two runs was kept.



SKETCH NO. 38 (Not To Scale)



SKETCH No. 39 (Not To Scale)

7 - 24. RUN No. 1. Q = 0.48 cusecs. No charge, d = 5.4", V = 1.22' per second, wave velocity = 1.08'/sec. at Fbo conditions. The flume was given a slope of 1 in. 700. Dunes were produced and they advanced rapidly at V^2/d = 8.20. At Fbo = 4.35, practically no grains were moving.

7 - 25. RUN No. 2. Q = 0.69 cusecs, No charge, d = 5-4", velocity = 1.53' per second, velocity of wave = 1.20' /second. Dunes were observed advancing fairly rapidly at $\frac{V^2}{d}$ = 9.10, a few grains were moving at Fbo = 5.20.

7 - 26. RUN No. 3. Q = 1.404 cusecs. No charge, d = 11", V = 1.53'/second, $\frac{V^2}{d}$ = 2.58, wave velocity = $\sqrt{gd}$ = 1.72'/sec.

A dune head started at about 4' - 2" with a height of about 2½" and moved down stream. The dune front had a steep adverse slope and consisted of sifted particles. The medium and the coarse particles were rolling up the upstream slope or were moving by saltation while some of the coarser particles were moving up the down stream slope of dune. The trough in front of the dune was deep and the lighter particles of the trough were continuously lifted up in suspension and thrown on the upstream slope of next dune and some were carried away to the next dune again. The conditions in front of the dune were those of scour-pattern and it could be seen that the particles were being swept away as if air were blowing over light particles and throwing them away. There appeared to be a whirl-pool action and suction in spite of the fact that the depth at the scoured place was 11" and over the crest of the dune was about 7½". That there was a pressure

difference at the front of the trough was apparent. The original depth at the dune crest at the point of observation was 5.25". It could be seen that the deposit over the original $3\frac{1}{2}$" bed was of sifted sand particles of larger diameter, vide Fig. 23.

7 - 27. As the dune front became steep, it fell down by sliding towards the natural angle of repose and it kept on advancing. The condition of scour pattern and movement pattern ahead of the second dune was exactly similar except that the depth of the trough was less. The same applied to the third one and by the time it reached the downstream end of the trough it got washed away.

7 - 28. As the dunes advanced, the trough portion ahead was filled up while the trough and dune crest kept on advancing. A profile of the dune was sketched on the glass wall of the flume and has been reproduced in fig. 3. The rate of progression of dunes is given in table 3. This run was continued for 48 hours and by that time the bed had settled to a condition of stability without dunes with a depth of 11" and a bed factor of 2.58 at zero charge.

7 - 29. <u>RUN No. 4</u>

The discharge from 1.424 cusecs of Run No. 3 was lowered to 1.12 cusecs and to an average depth of 5.5", four dunes appeared and moved fast. The discharge therefore was regulated to 1.00 cusecs and two dunes appeared moving. The bed movement developed the same pattern as in Run No. 3 - but the trough depth was much less. The dune front had an

adverse slope ranging from 50° to 55°, the heavier particles forming the down stream slope; the medium and finer particles kept leaping over the crest and the finer ones were lifted up and thrown from the trough to the upstream slope of next dune and the medium and heavier particles moved up the slope by rolling and saltation.

7 - 30. In this case also too many dunes developed, therefore, the discharge was raised to 1.264 cusecs. The depth was about 8.25", and the bed kept advancing with small dunes. It was further observed that the scour-pattern alternated from side to side, i.e. when one side had scoured to a deeper bed than the other side, then in the next forward region the dune and trough developed on the opposite side. This might also have been due to the entry conditions. This run ultimately settled to a zero bed factor of 3.94 while no grains were moving. (Ref. Table 1 Appendix A).

7 - 31. <u>RUN NO. 5 to RUN NO. 11</u> These were run with decreasing from 1.264 cusecs to Q = 0.32 cusecs and again for 0.864, 0.656 and 0.5056 cusecs (without charge). The results are given in Table No. 1.

7 - 32. <u>RUN NO. 12 Q</u>= 0.386, C = 9.15% per thousand. For dune length, height and their rate of progression vide table 3.

7 - 33. The first dune that formed kept on moving and when it has travelled some distance a second one formed 18" behind the first one. The height of

the second dune was less than the height of the first. Coarser particles were at the dune front on the reverse slope and the finer ones were lifted up from the trough ahead of the main dune and deposited on the slope of the next dune. All other characteristics were exactly similar as described for Run No. 3 & 4.

7 - 34. When the trough depth were considerable, the velocity of the front dune was small which indicated that a second dune upstream of the first one was likely to appear. The height and length of the dune appeared to be a function of the size of the materials, the depth, the velocity of channel and of charge. The dune velocity or its rate of progression was not uniform. As soon as the length of dune became considerable say about 45" and the depth of the trough was comparatively great, the dune came practically to a stop and a secondary dune formed on its back at an intermediate place; the rate of progression of this secondary dune was rather faster and they ultimately caught up with the main dune and the combined one kept on its forward travel. The entire flume thereafter was full of dunes usually at an average spacing of 43" with secondary dunes inbetween when the dune length tended to be greater than 45". The rate of advance of the secondary dune was 4" in five minutes approximately.

7 - 35. This run was considered to have reached a regime condition when the bed movement showed a uniform condition, of having about 3 nos of main dunes with secondary ones in between them depending on the length of the main dunes.

7 - 36. Although it could not be ascertained whether the cause of dune formation was unevenness of bed which caused eddies and turbulence and caused bedmovement and formation of dunes - or dune formation was due to excess charge in the flow which in its turn formed a trough ahead of it and thus created conditions for boils, swirls and eddies due to change of direction of the component forces from direction parallel to bed to inclined direction, it was, however, apparent that the formation of a dune head was a necessary condition for starting a series of dunes on the bed. Their behaviour and formation though seemingly erratic seemed to depend upon the conditions of filling up hollows and evening out the heights on the bed. They condition themselves upon the local unevenness and on the rates of progression of the ones ahead of them.

7 - 37. RUN 13 Similar to that of 12. - vide fig. 40.

7 - 38. RUN 14 $Q = 0.384$, $C = 27.50$. The position of the dunes at one instant is given in Fig. 41.
It would be seen that the forward one is 47" long while the one behind is 60" long having two small dunes 20" to 22" apart.

7 - 39. RUN 15 $Q = 0.384$, $C = 48.7$. The water surface was wavy. The depth varied from 2.5 to 2.75" according as a dune passed a section. There were 4 to 5 nos of dunes at any one instant and the length of dunes was about 16". When the number of dunes was 3, the length of dune was about 30". When the forward dune came to a stop, the one immediately behind accelerated till it caught up with the forward one. It would therefore

appear that the assumption of stable uniforum velocity is not applicable to dune movement of any appreciable height. For rate of progression length and height of dune vide table 3 and fig. 42.

7 - 40. <u>RUN 16</u> Q = 0.256, C = 10.4[illegible] per ‰

Small bed dunes formed on the bed. Sometimes bed dunes were forming and sometimes there were none on the bed. No measurements of dunes were taken as they were rather small. The bed factor at the working regime condition was 9.00.

7 - 41. <u>RUN 17</u> Q = 0.256 cusecs. C = 31[illegible] per thousand

Two dunes formed at 68" apart and in between these two large dunes, small ones developed. Bed in front of dune was of long scour pattern. The rate of progression of dunes are given in table 3, appendix A. Measurements of dune details were not taken as they were not of proper shape or magnitude. A profile of dune however after the experiment had been concluded is shown in fig. 43. The bed factor at working regime condition was 12.30.

7 - 42. <u>RUN 18</u> Q = 0.256 cusecs. C = 45.2[illegible] per ‰

The flow established itself in three hours. The depth varied from [illegible].0 to 1.90". The dunes were not of any appreciable height. All the grains were moving and there was extreme riffling and the bed appeared cloudy. There were dunes at times and none at others. The water surface was wavy when a dune passed a section and was comparatively smooth when a dune had moved some distance from the section. The bed factor was 16.30.

7 - 43 RUN 19 Q = 0.256, C = 63.0% per thousand. V^2 /d from 18.2 to 23.6 and depths between 1.8 to 1.70".

Bed was slightly aggrading. There were rather flat dunes on bed and extreme riffling all along. The front of the dunes appeared to be scoured. The mean bed factor was 20.90.

7 - 44. RUN 20 The discharge for this run was 0.33 cusecs and the flume was run without charge for about 18 hours after which a charge of C = 5.67% ‰ was introduced. Grains were moving on the bed without forming dunes and ultimately the bed developed small dunes all over at bed factor 9.30.

7 - 45. RUN 21 Q = 0.336 cusecs, C = 21.80 percent per thousand. Small dunes formed and were advancing. The surface of water was wavy. The depth was oscillating between 2.40" and 2.55". The dune profile that was obtained after completion of the run is shown in fig. 44.

7 - 46. RUN 22 Q = 0.328 cusecs, C = 29.80% per ‰

Small dunes formed - surface of water was wavy. Depth of flow varied between 2.45" and 2.40". The bed factor was 13.03.

7 - 47. RUN 23 Q = 0.328 cusecs, C = 40.60% per ‰

Four small dunes formed on the bed and kept on moving. The surface of water was wavy and the depth of flow varied between 2.27" and 2.35". The bed factor at the working regime condition was 15.26.

CHAPTER VIII

ANALYSIS OF EXPERIMENTAL RESULTS

8 - 1. Accepting Blench's line of attack, advantage will be found in writing all legitimate non-dimensional groups for scrutiny, and in deliberately choosing ones that will throw light on possible extensions to presently accepted equations whose data kept certain variables practically constant.

We may then write:

$$d,\ gS,\ \tau_b,\ \tau_s, = \text{fns}\ (b, C, D, Q, g, \nu, \rho_s, \rho_f) \quad - - - - (1)$$

as the statement that, when a discharge Q, of fluid with kinematic viscosity ν and mass density ρ carrying a bed load charge C of material of size D and mass density ρ_s is allowed to adjust to equilibrium in a flume of fixed breadth b, then adjustment results in a definite d, gS, and bed and side mean shear stresses τ_b and τ_s. gS is used instead of S, since "S" has no physical relevance except as a measure of energy gradient. Since Q = bdv, we may replace Q by V in equation (1).

To make 'd' non-dimensional we may divide by V^2/g to obtain the conventional Froude number, or by b or D or by $\left(\frac{\nu g}{g}\right)^{2/3}$ to obtain an unconventional Froude number, or may convert to a Reynold's number using V or $(\nu g)^{1/3}$. These devices show how it is possible to expand on the conventional methods of making gS and τ non-dimensional by dividing by $\frac{V^2}{d}$ and by ρV^2 respectively.

8 - 2 By conventional manupulations of equation - (1) from which ρ is omitted for simplicity, the foll wing interesting equations are obtained: -

$$\frac{V^2}{gd} = fn\left(\frac{VD}{\nu},\ C,\ b/d,\ \sqrt[3]{g\nu}.\frac{D}{\nu}\right) - - - - - (2)$$

$$\frac{V^2}{gd} = fn\left(\frac{D}{d},\ C,\ \frac{b}{d},\ \sqrt[3]{g\nu}.\frac{D}{\nu}\right) - - - - - - (3)$$

we may write also: $V^2/gd = fn\left(\frac{D}{d}, C, \frac{b}{d}, \frac{VD}{\nu}\right)$----(4) in which V is written for $\sqrt[3]{g\nu}$ such that the last non-dimensional term in equation (3) becomes $\frac{VD}{\nu}$ which may be called as particle Reynolds' number.

8 - 3 As both turbulence and viscosity play important part for bed -'incipient - condition' at bed factor zero, i. e., bed factor at zero charge, the parameters F_{bo} against $\left(\frac{D}{d}\right)$ and $\left(\frac{VD}{\nu}\right)$ appear important if $\left(\frac{b}{d}\right)$ is neglected as pointed out by Blench. (Ref. 26) though $\left(\frac{b}{d}\right)$ seems physically relevant.

8 - 4 Attempts at correl tion therefore have been made as follows:

(a) Fig. 45 shows plot of F_{bo} against Q.

(b) Fig. 46 shows plot of F_{bo} against d.

(c) Fig. 47, 48, 49 shows plot of F_b against C.

(d) Fig. 50 shows plot of $\frac{Fb - Fbo}{Fbo}$ against C

(e) Fig. 51 shows plot of Fbo against $(\frac{L}{d})\ g \cdot (\frac{\rho_s - \rho}{\rho})$

(f) Fig. 52 shows plot of Fbo against $(\frac{L}{d})^{1/3}\ (\frac{VD}{\nu})^{1/3}$

It would be at once apparent from the Fbo versus Q curve that Fbo decreases towards what we might expect from the rough Lacey rule as discharge increases. From Fig. 45 it is seen that at a discharge of 1.42 cusecs the bed factor zero = 2.58 while for a discharge of 0.48 cusecs it is 4.85. It may also be noted that, as discharge increases, the charge at which dunes form becomes less and less, pointing to the possibility that dunes might form and keep themselves at vanishingly small charge.

CHAPTER IX

SPECULATIVE POSSIBILITIES

9 - 1. A plot of $\frac{Fb - Fbo}{Fbo}$ against 'C' in log log paper gives an equation

$Fb = Fbo\ (1 + ac^{n}) = Fbo\ (1 + 0.15c^{0.7})$ --(5) Fig. 50 for 1.70 mm. gravel

This equation when compared with plotting by Blench and Erb of Gilbert data shows close resemblance. The index of 'C' shown in fig. 50 is 0.7 whereas that obtained from Blench's plotting is 0.77.

9 - 2. A plot of Fbo against $\left(\frac{VD}{\nu}\right)^{1/3} \cdot \left(D/d\right)^{1/3}$ gives the equation

$Fbo = 1.0\ \left(\frac{VD}{\nu}\right)^{0.80} \left(\frac{D}{d}\right)^{0.80}$ - - (6) Fig. 52 for 1.70 mm. gravel

9 - 3. Fig. 53 shows a plot of San Luis Valley Canal data Ref. 27 for gravels from 0.83" to 3.23" median diameter for the 1952 flood which was a much lower flood than 1953 one. If the conditions of this flood are accepted as those for Fbo condition, the following equation is obtained.

$$Fbo = 0.42\ \left(\frac{VD}{\nu}\right)^{0.28} \left(\frac{D}{d}\right)^{0.28} \quad \text{- - (7) Fig. 53}$$

9 - 4. Fig. 54 gives plot of Fbo against $\left(\frac{VD}{\nu}\right)^{1/3} \cdot \left(\frac{D}{d}\right)^{1/3}$ - - for 0.45 mm. to 0.83 mm. median diam. sand from the 'Simons and Bender data' for canals (Ref. 12). The resulting equation is $Fbo = 7.0\ \left(\frac{VD}{\nu}\right)^{1.5} \cdot \left(\frac{D}{d}\right)^{1.5}$ --(8) Fig. 54.

It is however quite possible that there may be some small charge conditions for 'San Luis Valley and Simons and Bender data' for canals but these would not materially affect the results.

9 - 5. Fig. 51 gives a plot of Fbo against $g\left(\frac{\rho_s - \rho}{\rho}\right) \cdot \left(\frac{D}{d}\right)$ for 1.70 mm. gravel

The following equation is obtained: -

$$F_{bo} = 90 \left(\frac{D}{d}\right)^{0.68} \text{ - - - - - - - - } (9)$$

While a plot of Sanluis Valley canal data would give an equation

$$F_{bo} = 35.0 \left(\frac{D}{d}\right)^{0.68} \text{ - - - - - - - } (10) \text{ - Fig. 51}$$

Whereas equation (9) is for laboratory gravel which might represent gravel about 10.00 mm. to 20.0 mm. in a prototype the equation (10) is for actual canals with gravel from 22.0 mm. to 83.0 mm. diam.

The above equations are highly speculative but they do suggest a rational approach.

CHAPTER X

CONCLUSIONS & RECOMMENDATIONS

10 - 1. Flume experiments with 1.70 mm. gravel (which may represent gravel of quite a large diameter in a prototype) show that: -

(a) At small charge amd small discharge, 1.70 mm. median diameter gravel does not form ripples, but it forms dunes as the charge is increased.

(b) After the formation of dunes, the bed characteristics follow the same pattern as those for sand.

(c) Dunes which have been formed on the bed of 1.70 mm. sand at small discharge are washed away if charge is discontinued.

(d) The bedfactor Fbo decreases as discharge increases, but the apparatus was not large enough to show the limiting value of Fbo.

(e) As discharge increases the charge necessary to form dunes tended to become less and less, but the apparatus was not large enough to show whether dunes form at vanishing charge when discharge exceeds some limits.

RECOMMENDATION

10 - 2. The results obtained suggest a complete program of work on the following lines: -

(i) Repeat and extend preceding experiments to discharge intensities $\gg$ 1.50 cusecs per foot in a flume long enough to eliminate entry and exit disturbance and permit measurement of slope, and broad enough to give a minimum $\frac{b}{d}$ ratio of 3.

(ii) Repeat with gravel graded to the log normal distribution of natural sand.

(iii) Repeat with large gravel.

(iv) Repeat with gravels prepared from materials of specific gravity markedly different from quartz.

(v) Repeat with various sands of natural constitution.

(vi) Repeat with uniformised sands.

Aim at plots showing contours of $\frac{VD}{\nu}$, $\frac{D}{d}$, $\frac{Vs}{V}$ and other likely parameters when adequate data have been obtained.

REFERENCE (BIBLIOGRAPHY)

1. "Regime analysis of laboratory data on bed load transport". T. Blench and R. Bryan Erb. La Houille Blanche No. 2. Mar. - April, 1957.
2. "On the formation of ripples". C. H. Darwin. Proceedings Royal Society of Lon , A. No. 892 Vol. 157, 1936. 594-620.
3. Discussion by G. F. Deacon of "Training of Rivers". L. F. Vernon Harcourt. Proceedings Institute of Civil Engineers London. Vol. CXVIII 1894.
4. "The Physics of Blown Sand and Desert Dunes". Brigadier R. A. Bagnold F.R.S. Proceedings Royal Society London, A, No. 892 Vol. 157. 1936. 594 - 620.
5. "Introduction to Fluvial Hydraulics". Serge Leliavsky. Constable and Company. London 1955. P. 17 - 19.
6. "Sand Mixtures and Sand Movement in Fluvial Models". H. Kramer. Trans. A.S.C.E. Vol. 100, 1935.
7. Discussion by L. G. Straub of "Sand Mixtures and Sand Movement in Fluvial Models". H. Kramer. Trans. A.S.C.E. Vol. 100, 1935.
8. "The Transportation of Debris by Running Water". G. K. Gilbert. U.S. Geological Survey Professional paper 86. 1914.
9. "Unwendung der Aehlichkeits mechanik under Turbulenz forschung auf die Geschiebbwegung" by A. Sheilds Mitteilungen der preussischen Versuchsanstalt fur wasserbau and Schiffbau. Heft 26, Berlin 1936.
10. "The Behaviour and Control of Rivers and Canals". C. C. Inglis Govt. of India, Central Waterpower Irrigation and Navigation Research Station Poona Research Publication No. 13. 1949.

11. "Turbulent transfer mechanism and suspended sediment in closed conduit channels". Hassan M. Ismail. Trans. A.S.C.E. Vol. 117. 1952.

12. "Resistance to flow in alluvial channels". D. B. Simons and E. V. Richardson. Proceedings A. S. C. E. Paper No. 2485. May 1960.

13. Discussion by Simons and Richardson of "Resistance Properties of Sediment - Laden Streams". Vito A. Vanoni and George N. Nomicos. Proceedings A. S.C. E. December 1959.

14. Discussion by Tiffany and Bentzel of "Sand Mixtures and Sand Movements in Fluvial Models". H. Kramer. Trans. A. S. C. E. Vol. 100, 1935.

15. "Mechanics of Sediment Ripple Formation". H. K. Liu. Proceedings A.S.C.E. Paper 1197, Vol. 83, April 1957.

16. "Introduction a l'etude de la saltation". P. Danel, R. Durand and E. Condalois. La Houille Blanche 1953, No. 6, English Translation Supp. No. 1. 1955.

17. "The River Klaralven. A Study of Fluvial Processes". A. Sundborg. No. 32 Inst. Hydr. Stockholm. 1956.

18. "Flow in Alluvial Channels in Sandy Mobile Bed" by Gerald Lacey - Proceedings Institution of Civil Engineers Vol. 9, January and April 1958.

19. "Special Observations of Bed-Load Movement in Lower Fraser River (tidal)" 1950 - 51 by T. Blench.

20. "Systematic Changes in the Beds of Alluvial Rivers". W. C. Carey and M. D. Keller. Proceedings A.S.C.E. Paper 1331. August 1957.

21. "Die Schwemmstofführung des Rheins und anderer Gewässer". Von W. Kresser, Österreichische Wochenschrift für den öffentlichen Baudienst. 1949.

22. "Der Flussbau". Von F. Kreuter (Handbuch der Ingenieur Wissenschaften pt. III, Vol. 6, fifth edition). Leipzig 1921.

23. "Über Schleppkraft und Geschiebebewegung". Von A. Schoklitsch, Leipzig und Berlin. 1914.

24. Discussion: Closure by A. Vanoni of "Resistance Properties of Sediment Laden Streams" by Vito A. Vanoni and George N. Nomicos. Paper 2489. Proceedings A.S.C.E. May 1960.

25. "Basic relationships of the transportation of solids in pipes". Experimental research R. Durand. Laboratoire Dauphinois d'Hydraulique, France. I. A. H. R. 1953.

26. "Regime Behaviour of Canals and Rivers". T. Blench. Butterworths Scientific Publications. 1957.

27. "Some factors affecting the stability of canals constructed in coarse granular materials". E. W. Lane and E. J. Carlson. I.A.H.R. 1953.

28. "Settling velocities of gravel, sand and silt particles". William W. Rubey. Vol XXV, American Journal of Science. April 1933.

29. "Formulas for the transportation of bed-load" H. A. Einstein. Trans. A.S.C.E. Paper No. 2140. 1942.

30. "Formulas for bed load transport" E. Meyer-Peter and R. Muller. I.A. H.S.R. Stockholm 7-9 VI. 1948.

31. "Discharge Formula for Straight Alluvial Channels" H. K. Liu and S. Y. Hwang. Proceedings A.S.C.E. Paper No. 2250. November 1959.

APPENDIX A

TABLES

TABLE NO. 1

(Experimental Results - 1.70 mm. Gravel Without Charge)

RUN NO.	DISCHARGE Q CUSECS	MEAN DEPTH 'd' ins	MEAN VELOCITY V FT/SEC.	V^2/d	TEMP °F	SLOPE 'S'	D/d x 10^2	$(\frac{D}{d})^{1/3}$	Remarks
1	0.48	4.35	1.325	4.85			1.54	0.25	Bed stable - Just active
2	0.69	5.40	1.53	5.20			1.24	0.232	Few grains moving Tb* conditions
3-a	1.424	9.93	1.72	3.58	70		0.68	0.190	A few grains moving - Tb* conditions
3-b	1.424	11.00	1.53	2.58			0.61	0.173	Bed stable - Just active
4	1.264	8.90	1.71	3.94	71		0.754	0.196	Tb* condition a few grains moving
5	1.04	7.52	1.66	4.40			0.89	0.207	Tb* condition a few grains moving
6a	0.948	7.00	1.51	3.92			0.957	0.212	Bed just getting active
6b	0.948	6.57	1.61	4.73			1.02	0.218	Tb* condition - a few grains moving
7-a	0.44	3.90	1.35	5.42			1.72	0.258	Tb* condition - a few grains moving
7-b	0.44	4.00	1.32	5.25			1.67	0.255	condition between Tb* and Tbo.
7-c	0.44	4.25	1.24	4.94			1.58	0.227	Tbo conditions
8-a	0.32	3.10	1.24	5.94			2.16	0.278	Slope increased by lowering weir to create bed activity.

TABLE NO. 1 (Continued)

(Experimental Results - 1.70 mm. Gravel Without Charge)

RUN NO.	DISCHARGE Q CUSECS	MEAN DEPTH 'd' ins	MEAN VELOCITY V FT/SEC.	V^2/d	TEMP °F	SLOPE 'S'	$D/d \times 10^2$	$(\frac{D}{d})^{1/3}$	Remarks
8-b	0.32	3.0	1.28	6.55			1.02	0.2178	Tb* conditions
9-a	0.864	6.45	1.605	4.80			1.04	0.218	
9-b	0.864	6.37	1.625	4.96		0.15/	1.05	0.218	
10-a	0.656	5.60	1.406	4.24			1.195	0.228	Tbo conditions
10-b	0.656	5.70	1.392	4.06			1.175	0.226	Bed inactive
10-c	0.656	5.25	1.50	5.15			1.30	0.2348	Tb* a few grains moving condition
11-a	0.5056	4.25	1.425	5.75			1.57	0.226	Tb - a few grains moving
11-b	0.5056	4.55	1.336	4.80			1.40	0.241	Tbo conditions

Tbo Condition - Bed Just getting active or movement just stopping

Tb* Condition - A few grains moving - Less than 3[illegible] per 1,000 of charge

TABLE NO. 2

EXPERIMENTAL RESULTS (WITH CHARGE) 1.70 mm. GRAVEL)

RUN NO.	Q IN CUSECS	MEAN DEPTH 'd' INCHES	MEAN VEL. V F /Sec.	V^2/d	MEAN V^2/d	TEMP ^oF	CHARGE 'C' % per %o	SLOPE 'S'	F_{bo}	$\frac{Fb - Fbo}{Fbo}$	REMARKS
12-a	0.384	3.13	1.48	8.42	8.51	70	9.15	0.15/60	5.0	0.702	Steady conditions 3 dunes
12-b	0.384	3.10	1.49	8.60			"	"			Steady-depth between 3.10 and 3.13"
13-a	0.384	3.00	1.54	9.50	10.35		20.85	0.2/60		1.07	DUNES
13-b	0.384	2.90	1.59	10.48			"				DUNES
13-c	0.384	2.85	1.62	11.08			"				Steady conditions DUNES
14-a	0.384	2.76	1.67	12.12	12.36		27.50	0.25/60	5.0	1.49	Marked with steady small dunes
14-b	0.384	2.73	1.69	12.60			"	0.20/60			Steady with small dunes
15-a	0.384	2.70	1.71	13.00	14.32		48.70		5.0	1.864	Steady-cloudy surface-with small dunes
15-b	0.384	2.60	1.775	14.55			"	0.25/60			
15-c	0.384	2.55	1.81	15.42			"				
16-a	0.256	2.35	1.35	9.25	9.00	70	10.40	0.125/60	5.28	0.698	
16-b	0.256	2.40	1.32	8.75			"	0.10/60			

TABLE NO. 2

EXPERIMENTAL RESULTS (WITH CHARGE) 1.70 MM. GRAVEL)

RUN NO.	Q IN CUSECS	MEAN DEPTH 'd' INCHES	MEAN VEL. V F /Sec.	V^2/d	MEAN V^2/d	TEMP °F	CHARGE 'C' % per %	SLOPE 'S'	F_{bo}	$\frac{Fb - Fbo}{Fbo}$	REMARKS
17-a	0.256	2.20	1.44	11.30	12.30		31.0	0.15/60		1.45	Dune-bed (small)
17-b	0.256	2.15	1.475	11.60			"				
17-c	0.256	2.10	1.51	13.0	12.30			0.15/60	5.28	1.45	
18-a	0.256	1.90	1.67	17.50	16.30		45.20			2.08	Small dunes -particles riffling-cloudy above bed
18-b	0.256	2.00	1.585	15.10							
19-a	0.256	1.80	1.655	18.20	20.90		63.0	0.20/60		2.94	Too much riffling Dunes-vanishing
19-b	0.256	1.70	1.865	23.60							
20	0.336	2.75	1.465	9.35	9.30		56.70	0.10/60	5.10	0.839	No dunes-grains moving
21	0.336	2.53	1.59	12.05	12.05	70	21.80	0.20/60		1.36	Dunes Advancing
22-a	0.328	2.45	1.61	12.60	13.03		29.80		5.11	1.55	Wavy
22-b	0.328	2.40	1.64	13.45							
23-a	0.328	2.30	1.71	15.50		70	40.6				Small dunes
23-b	0.328	2.27	1.73	15.88	15.26			0.22/60		1.99	4 Nos.
23-c	0.328	2.35	1.68	14.40							

TABLE NO. 3

(SHOWING DUNE LENGTH, HEIGHT AND SPEED, 1.70 MM. GRAVEL)

RUN NO.	LENGTH TRAVELLED IN INCHES	TIME TAKEN SECONDS	SPEED OF DUNE-INCH PER SEC.	NO. OF DUNE (MAIN)	LENGTH OF DUNE IN INCHES	HEIGHT OF DUNE	REMARKS
3	13"	1631.40	0.008	2	(a)-51" (b)-33½"	(a) 2.75" (b) 1.01"	Vide sketch No. 33 Unstable condition (without charge)
13	6"	1519.0	0.004	2	(a)-54" (b)-36"	(a) 0.3" (b) 0.19"	2 Dunes moving - a third appears before second one vanishes.
14	-	-	-	2	(a)-40" (b)-47"	- -	These larger dunes had smaller ones on their back at spacing of 11" to 15" vide sketch no. 40. Usually a steady condition was marked by 2 large dunes with small ones at 20" to 22" on the back of large ones.
15	11.75"	80.2	0.146	4 to 5	15" to 25"	0.4" to 0.25"	A steady condition was
	18"	138.2	0.130	4 to 5	15" to 25"	0.4" to 0.25"	marked by dunes all over the bed. 4 to 5 nos.
17	14".0	229.0	-	2	63" to 70"	-	The 2 large ones were accompanied by smaller ones vide sketch after run. Fig. 43.
21	-	-	-	2	70" to 72"	0.25" to 0.125	With small dune at 40" vide sketch no. 44.

TABLE NO. 4

(CHARGE AND RATE OF CHARGE FOR 1.70 MM. GRAVEL)

RUN. NO.	DISCHARGE 'Q' CUSECS	DISCHARGE IN POUNDS/SEC	CHARGE IN GRAMS	TIME IN MINUTES	CHARGE IN PER CENT PER THOUSAND % PER ‰	REMARKS
12	0.384	24.6	800	13	9.15	
13	0.384	24.6	1690	12	20.85	
14	0.384	24.6	1110	6	27.50	
15	0.384	24.6	2200	7.50	48.70	
16	0.256	16.50	340	7.25	10.40	
17	0.256	16.50	1090	8.00	30.30	Average 31.0% per ‰
	"	"	715	5.00	21.70	
18	0.256	16.50	1225	6.00	45.20	
19	0.256	16.50	1415	5.00	63.0	
20	0.336	21.0	295	9.00	5.70	
21	0.336	21.0	1250	10.40	21.80	
22	0.336	21.0	1318	8.0	29.80	
23	0.336	21.0	1380	6.0	40.60	

TABLE NO. 5

(COMPUTATION - 1.70 MM. GRAVEL)

RUN NO.	'd' in feet	V in ft/sec.	$g.\frac{\rho_s-\rho}{\rho}$	$g.\frac{\rho_s-\rho}{\rho}.(\frac{D}{d})$	$\frac{VD}{\nu}$	$\left(\frac{VD}{\nu}\right)^{1/3}$	$\frac{D}{d} \times 10^2$	$(\frac{\nu}{d})^{1/3}$	$(\frac{VD}{\nu})^{1/3} (\frac{\nu}{d})^{1/3}$	$\frac{V^2}{d}$	REMARKS
1	0.362	1.325	52.5	0.81	420	7.50	1.54	0.25	1.88	4.85	For
3b	0.916	1.53	"	0.32	650	8.66	0.61	0.173	1.50	2.58	Bed Factor
6a	0.584	1.51	"	0.502	620	8.55	0.957	0.212	1.82	3.92	Zero Conditions
6b	0.33	1.32	"	0.88	410	7.48	1.67	0.255	1.91	5.25	"
10b	0.475	1.39	"	0.867	485	7.87	1.65	0.254	1.78	4.06	"
11b	0.379	1.336	"	0.735	418	7.57	1.40	0.241	1.825	4.80	"
2	0.45	1.53	"		866	9.55		0.232	2.22	5.20	For a
3a	0.829	1.72	"		975	9.95		0.190	1.89	3.58	few grains moving
4b	0.741	1.71	"		970	9.90		0.196	1.94	3.94	condition of
5	0.626	1.66	"		940	9.80		0.207	2.025	4.40	a very small
6b	0.657	1.61	"		912	9.70		0.218	2.118	4.73	charge
7a	0.325	1.35	"		765	9.13		0.258	2.358	5.62	less than
8a	0.258	1.24	"		704	8.92		0.272	2.48	5.94	4 percent
9a	0.538	1.605	"		910	9.68		0.218	2.12	4.80	"
10c	0.437	1.50	"		850	9.45		0.235	2.22	5.15	"
11a	0.354	1.425	"		807	9.30		0.226	2.10	5.75	"

TABLE NO. 6

(COMPUTATION FROM SAN LUIS VALLEY DATA FOR STABLE CANALS)

MEDIAN SIZE INCHES	'd' IN FEET	V FT. PER SEC.	$\frac{VD}{\nu} \times 10^{-5}$	$\left(\frac{VD}{\nu}\right)^{\frac{1}{4}}$	$\frac{D}{d}$	$\left(\frac{D}{d}\right)^{\frac{1}{4}}$	V^2/d	$\left(\frac{VD}{\nu}\right)^{\frac{1}{4}}\left(\frac{D}{d}\right)^{\frac{1}{4}}$			REMARKS
3.23	4.09	4.80	1.29	18.92	0.067	0.507	5.65	9.55	52.50	3.54	
3.03	2.43	3.91	1.05	18.20	0.104	0.568	6.28	10.20	"	5.45	
2.99	2.68	4.65	1.25	13.80	0.0935	0.552	8.05	10.35	"	4.90	
1.65	1.61	3.57	0.492	14.86	0.0856	0.544	7.90	8.06	"	4.50	
1.50	1.60	3.68	0.46	14.65	0.078	0.528	8.45	7.82	"	4.10	
0.83	1.72	2.21	0.153	11.60	0.0402	0.452	2.86	5.22	"	2.14	
1.89	1.69	2.71	0.428	14.30	0.0932	0.552	4.35	7.65	"	4.90	
2.12	2.25	4.36	0.77	16.65	0.0785	0.53	8.46	8.85	"	4.12	
2.52	0.51	1.52	0.317	13.64	0.412	0.801	4.64	10.96	"	2.16	
1.54	0.56	1.34	0.172	11.45	0.229	0.691	3.20	7.92	"	1.20	

WATER TEMP. NOT GIVEN (ASSUMED) $\nu = 1.0 \times 10^{-5}$

TABLE NO. 7

(COMPUTATION FROM SIMONS AND BENDER DATA FOR STREAMS)

MEDIAN DIAM.	TEMP. OF	'd' in feet	V in feet per second	$\frac{VD}{\nu}$	$\left(\frac{VD}{\nu}\right)^{1/3}$	$\frac{D}{d} \times 10^4$	$\left(\frac{D}{d}\right)^{1/3}$	$\nu \times 10^5$	$\frac{V^2}{d}$	$\left(\frac{VD}{\nu}\right)^{1/3}\left(\frac{D}{d}\right)^{1/3}$	REMARKS
0.58	79	2.92	2.42	460	7.7	6.50	0.0865	0.93	2.0	0.665	
0.805	74	7.66	1.79	472	7.78	3.44	0.07	1.01	0.418	0.5446	
0.617	77	2.63	1.58	320	6.98	7.69	0.092	0.97	0.95	0.64	
0.465	79	2.91	1.67	260	6.38	5.23	0.081	0.93	0.955	0.516	
0.715	73	3.31	2.42	565	8.30	7.06	0.089	1.02	1.77	0.74	
0.246	82	3.67	1.86	150	5.30	2.20	0.061	0.95	0.945	0.323	
7.00	62	7.88	2.26	5160	15.24	29.10	0.143	1.185	0.65	2.18	
7.60	61.5	5.73	2.57	6430	13.50	43.60	0.163	1.19	1.15	2.04	

APPENDIX B

LIST OF SYMBOLS

Symbols	Description	Dimensions	Units	Remarks
a	A constant	C	-	
b	Mean width of bed	L	ft.	
C	Charge	parts in percent per thousand	-	
d	Mean depth	L	ft.	
g	Acceleration due to gravity	L/T^2	ft/sec^2	
l	A length	L	ft.	
r	Hydraulic radius	L	ft.	
t	Time	T	sec.	
V	Mean velocity	L/T	ft/sec.	
D	Median diameter of Particles	L	ft.	
Q	Discharge	L^3/T	cusecs, cfs.	
S	Slope of energy gradient equal to water surface slope in steady uniform flow	O	-	
Fr	Froude number	O	-	
ρ	Mass density of water	M/L^3	$slug/ft^3$	
ρ_s	Mass density of bed-load	M/L^3	$slug/ft^3$	
γ	Specific weight of water	M/L^2T^2	lbs/ft^3	
γ_s	Specific weight of bed-load	M/L^2T^2	lbs/ft^3	
τ_b	Shear stress along bed	M/LT^2	lbs/ft^2	

LIST OF SYMBOLS CONT.

SYMBOLS	DESCRIPTION	Dimensions	Units	Remarks
τ_s	Shear Stress along sides	M/LT^2	lbs/ft^2	
ν	Kinematic viscosity	L^2/T	ft^2/sec	
F_b	Bed factor	L/T^2	ft/sec^2	
F_{bo}	Bed-factor at vanishing charge or zero bed factor or bed factor zero	L/T^2	ft/sec^2	
V_*	Shear velocity	L/T	ft/sec	
V_s	Fall velocity of Particles	L/T	ft/sec.	

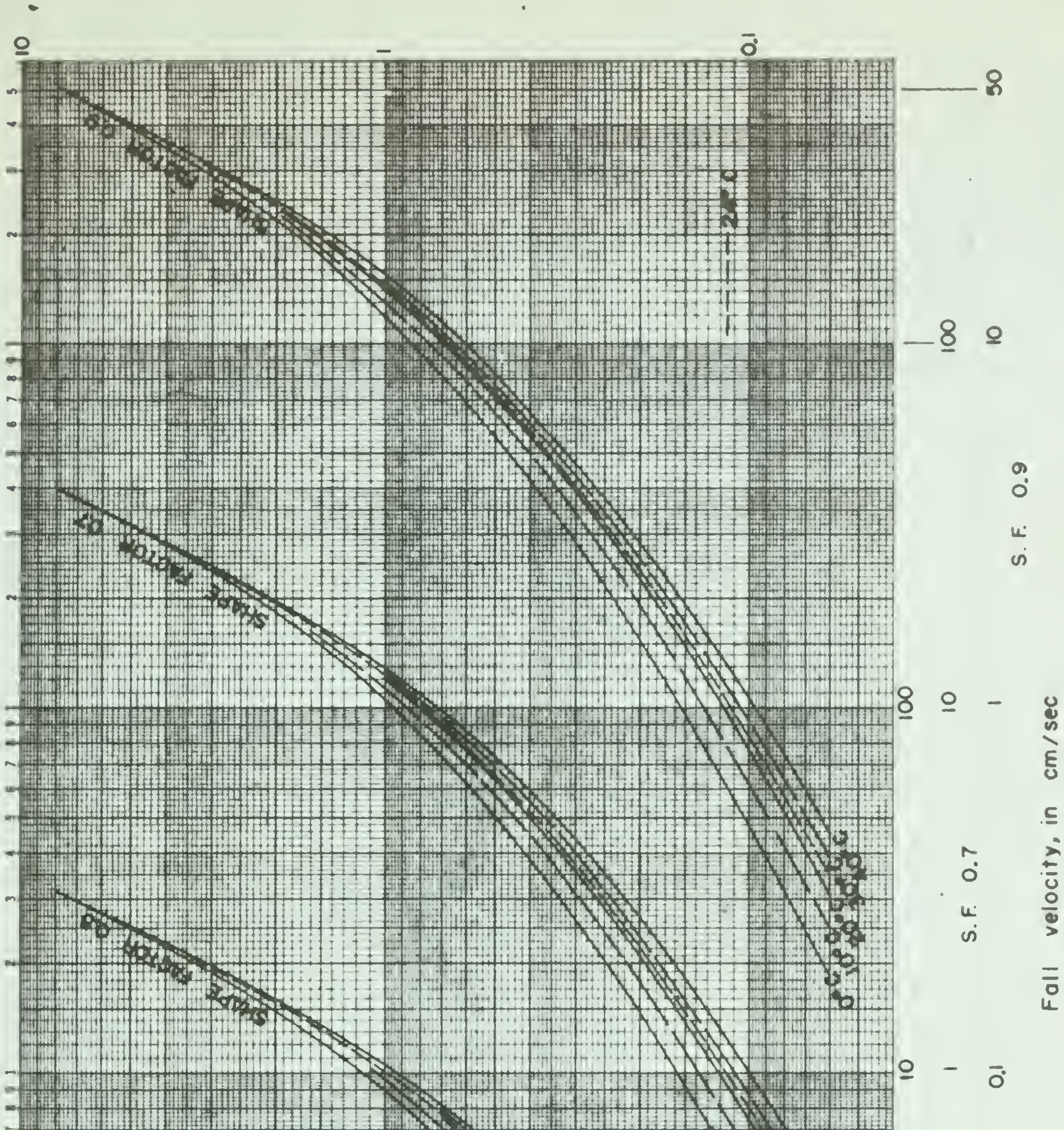


FIG. 2—RELATION OF NOMINAL DIAMETER AND FALL VELOCITY FOR NATURALLY WORN QUARTZ PARTICLES FALLING ALONE IN QUIESCENT DISTILLED WATER OF INFINITE EXTENT

FIG. 1 (AFTER I.A.C.W.R. REPORT NO.12 1957)

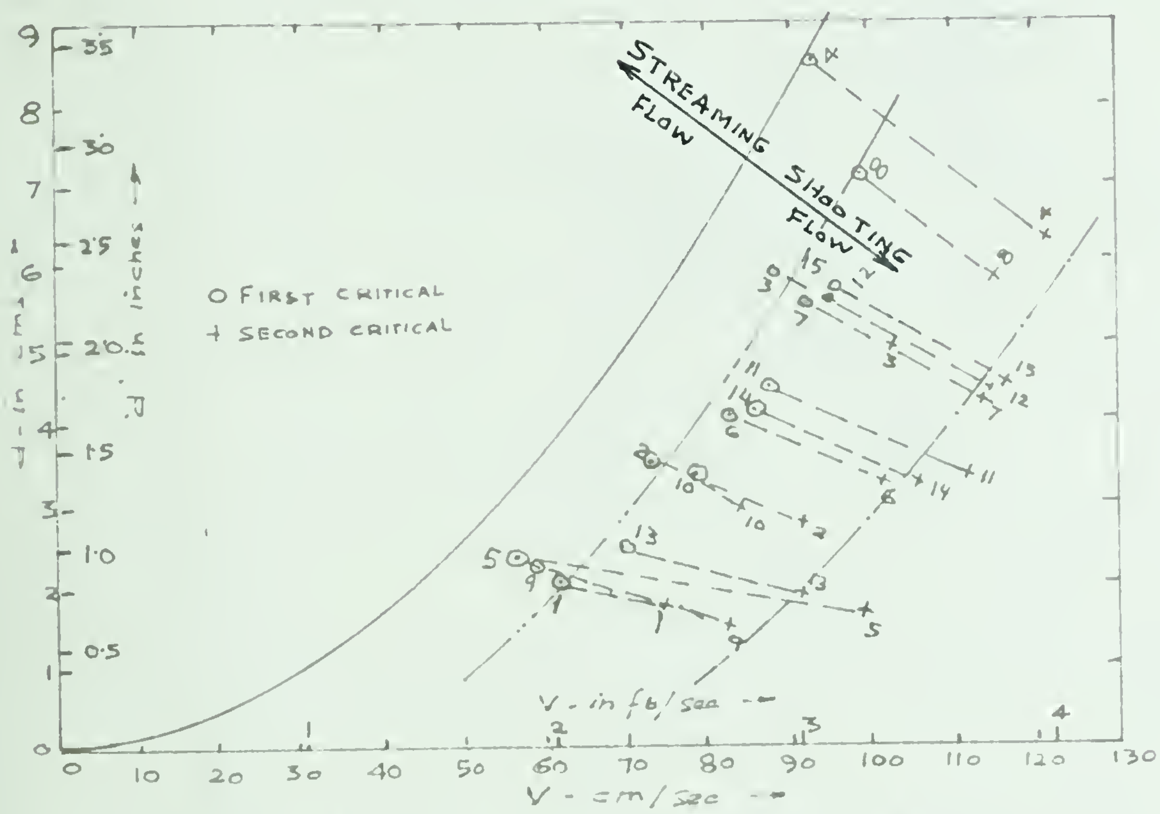


FIG-2 CRITICAL POINTS IN RIFFLE DEVELOPMENT
(AFTER KRAMER)

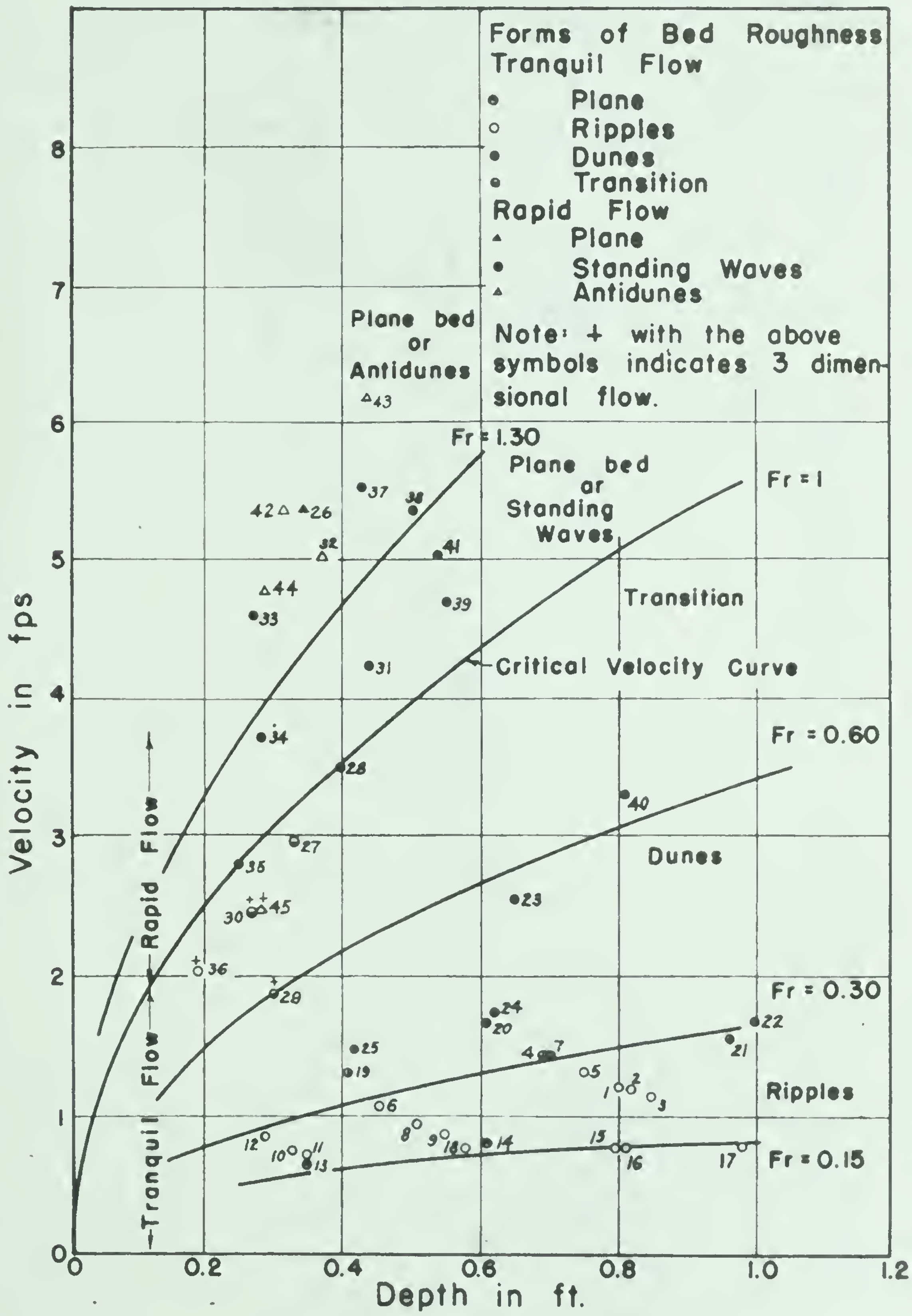


FIG. 8.—VARIATION OF VELOCITY V WITH DEPTH D

FIG. 3 (AFTER SIMONS & RICHARDSON)

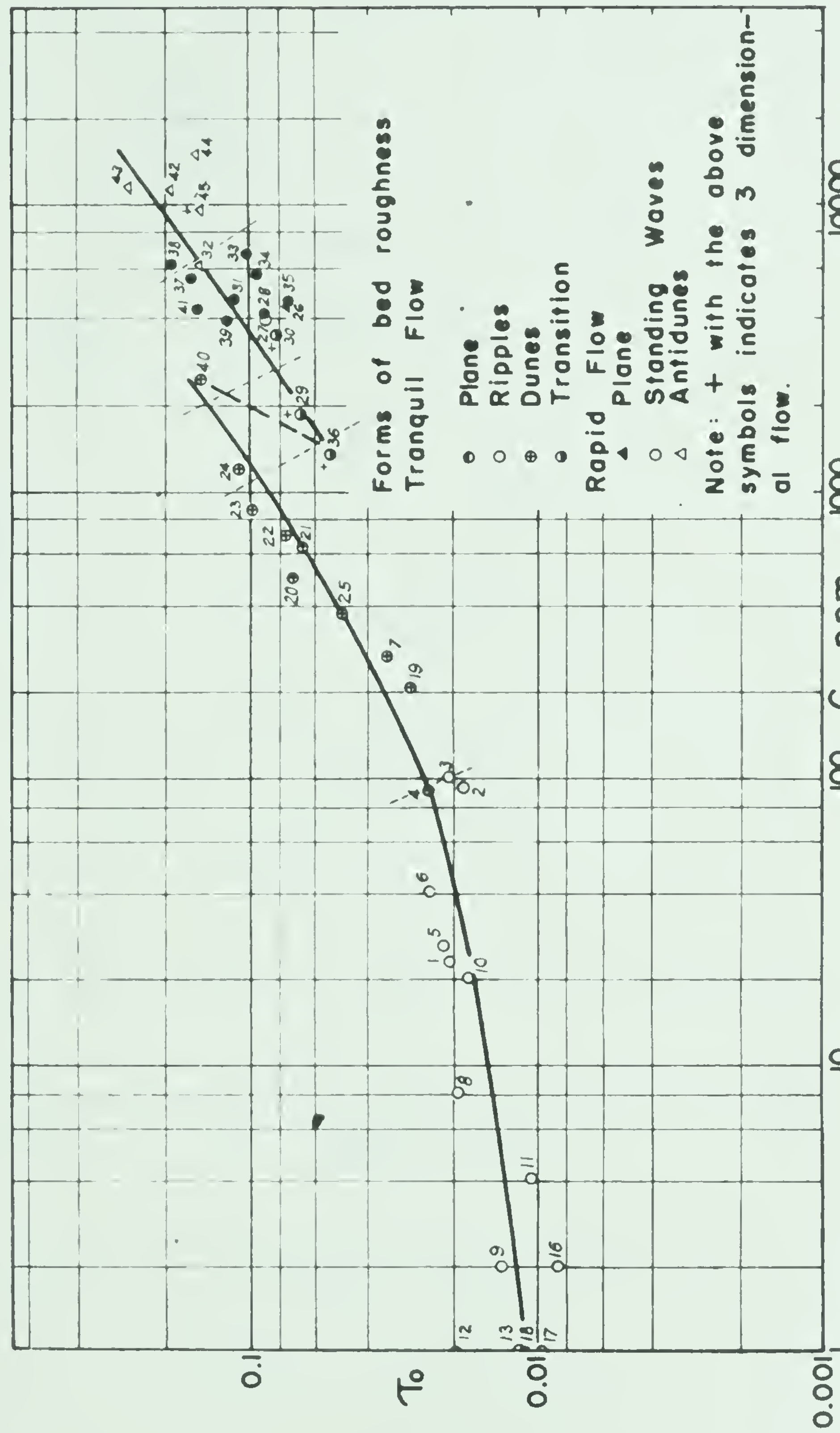


FIG. 9.—VARIATION OF τ_0 AND C_T PPM

FIG. 4 (AFTER SIMONS & RICHARDSON).

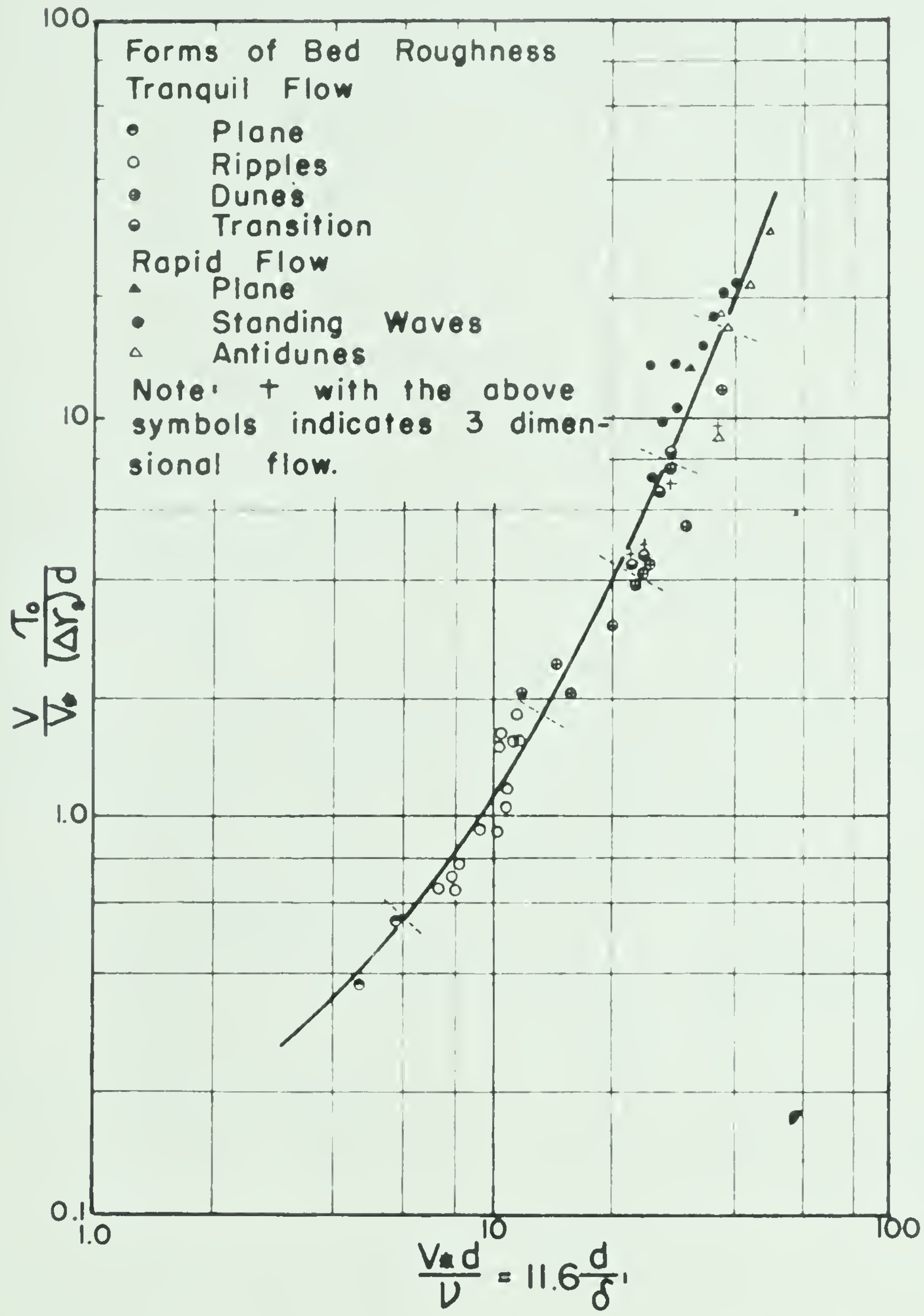


FIG. 10.—VARIATION OF $\frac{V}{V_*}\frac{\tau_0}{(\Delta\gamma_s)d}$ WITH $\frac{V_* d}{\nu}$

FIG. 5 (AFTER SIMONS & RICHARDSON)

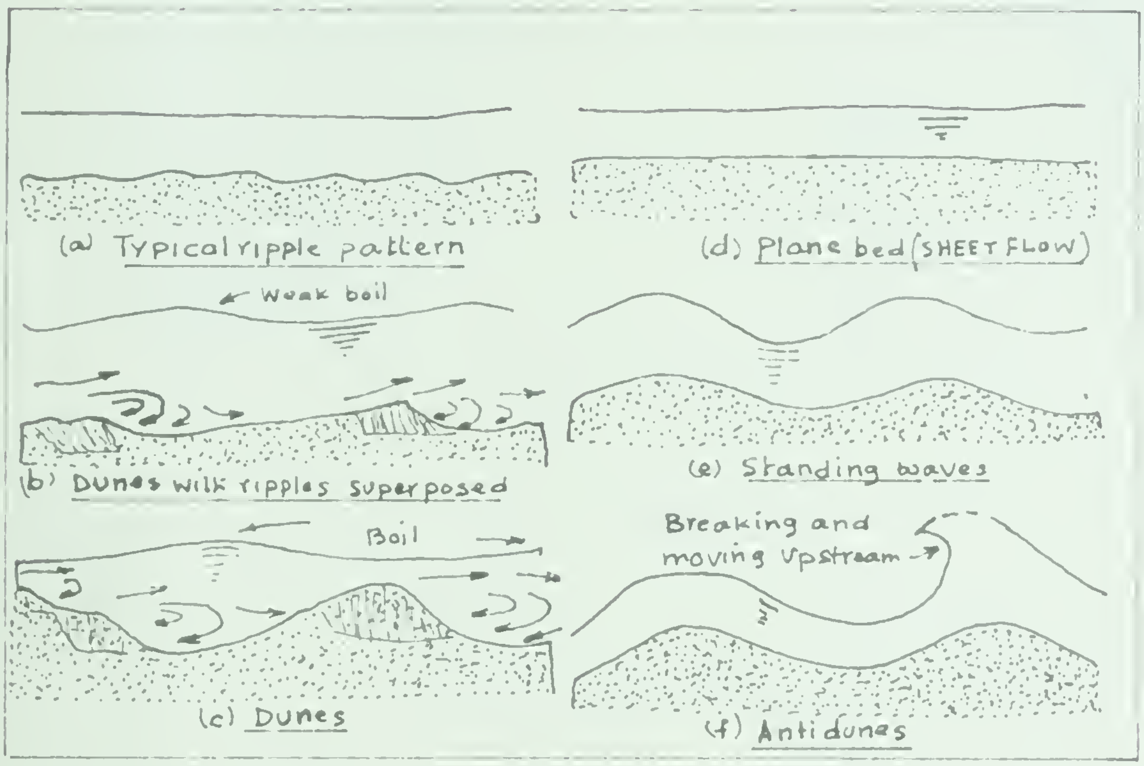
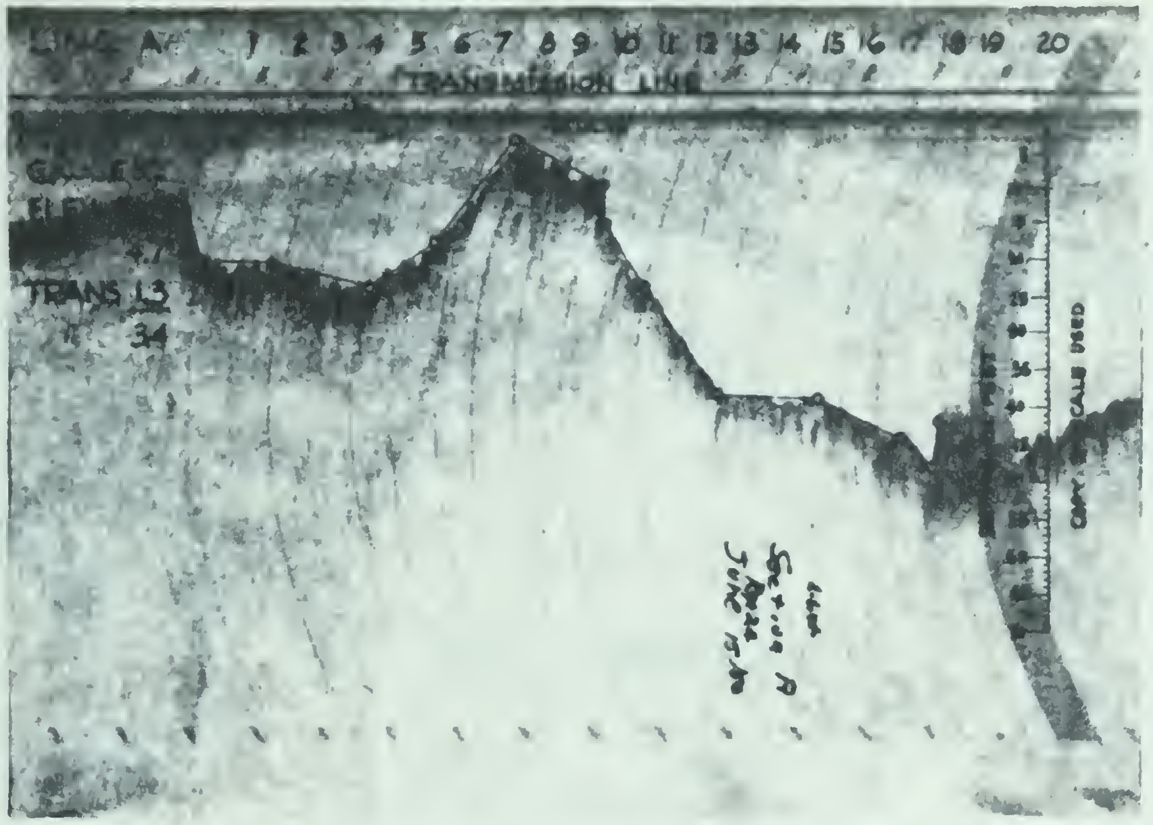


FIG 6. DEFINITION SKETCH (FORMS OF BED ROUGHNESS).

FIGURE I. ECHO SOUNDING RECORD - RANGE "A"



PHOTOSTATIC REPRODUCTION - 0.632 X FULL SIZE.

TABLE I. FIELD RECORD OF FIXES-RANGE "A"

SECTION A
RGE 24

JUNE 15 1950
TIME 13 35

GAUGE 9.2'

GERRY 23-24 °	'	HARRY 24 26 °	'	FLAG
24	12	43	45	
24	39	45	12	
26	19	47	00	
27	43	48	49	
29	38	50	55	
31	26	53	13	
33	55	55	52	
35	35	59	00	
38	05	61	36	
41	15	64	18	
46	02	67	41	
49	33	70	34	
53	52	72	45	
57	46	76	21	
63	20	79	53	
66	49	81	50	
70	32	83	09	
74	29	85	32	
78	17	87	27	
86	52	88	35	

FIG 7 (AFTER BLENCH)

BED WAVE FORMATIONS
AS RECORDED ON
HUGHES RECORDING ECHO SOUNDER

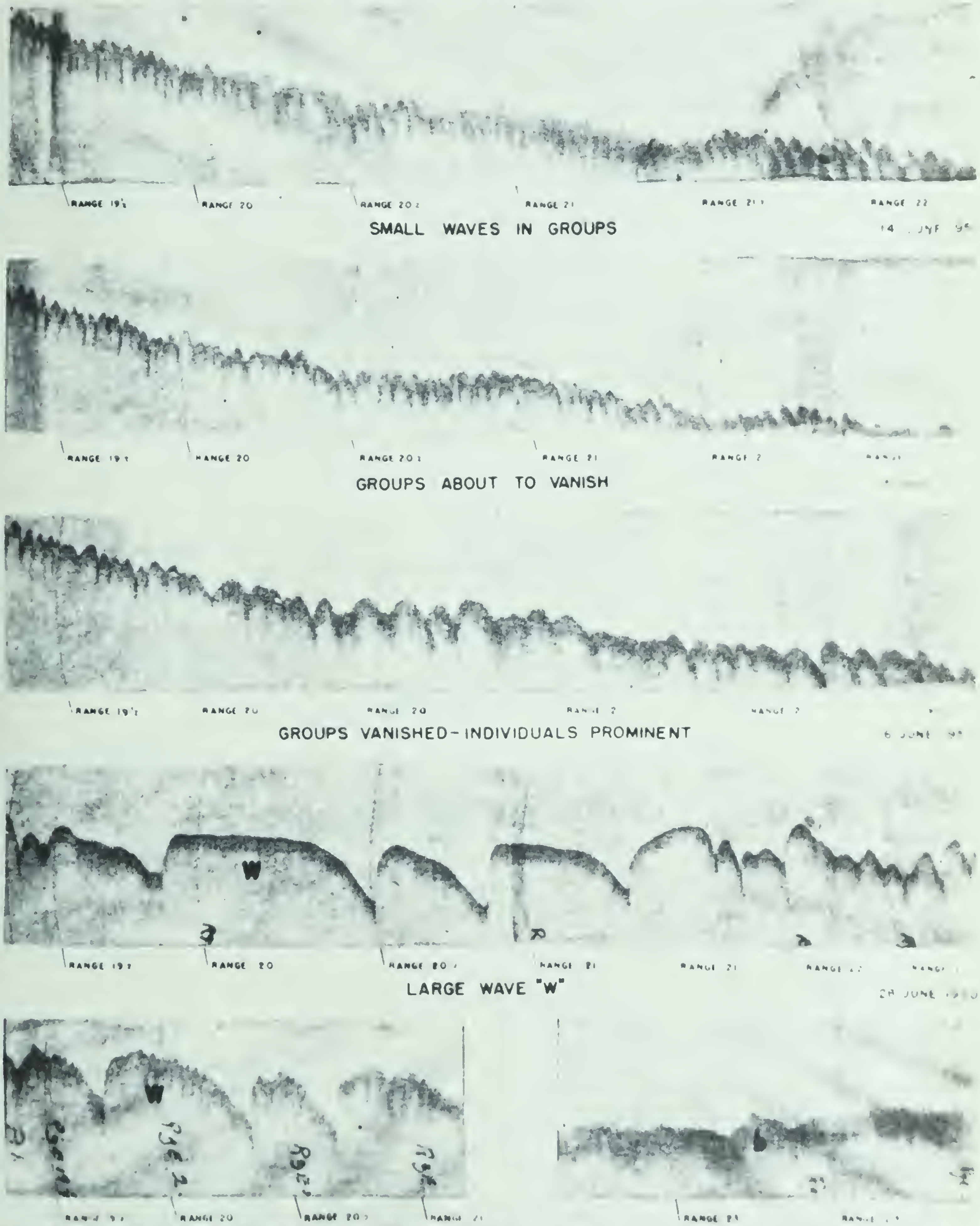
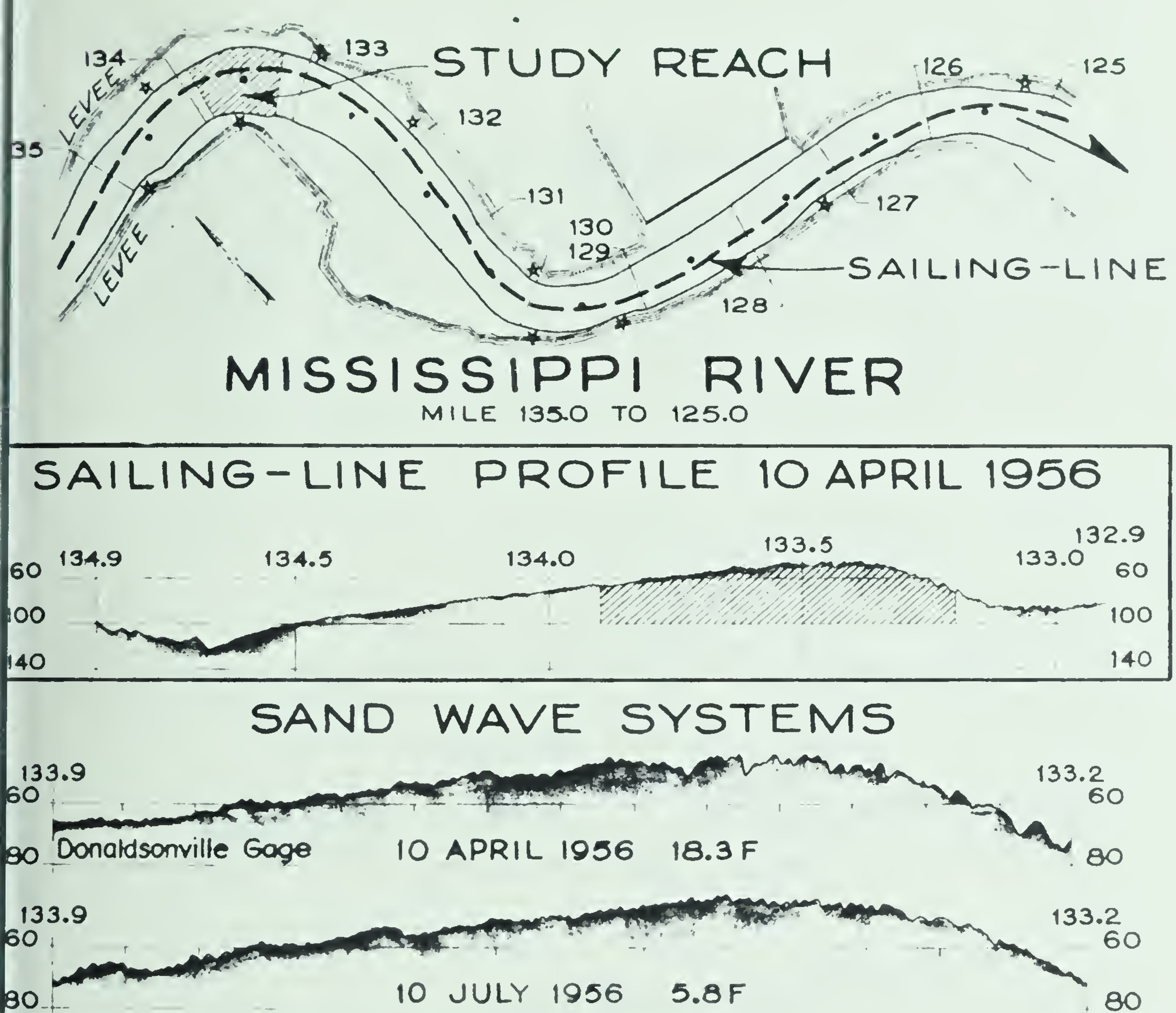


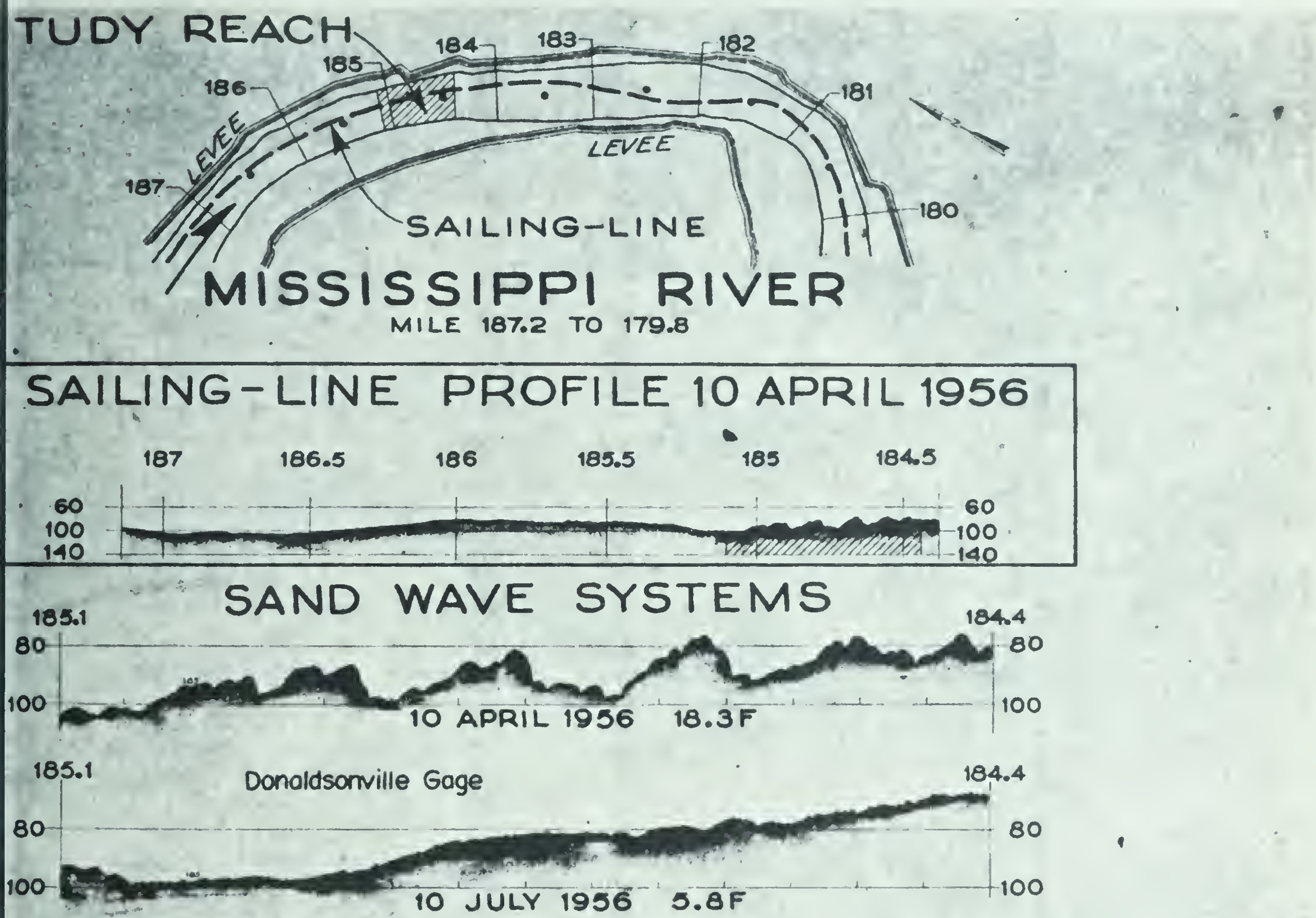
FIG 8 (AFTER BLENCH)



ASCE CAREY - KELLER 1331-11

5

FIG. 9 (AFTER CAREY & KELLER)



8

FIG. 10 (AFTER CAREY AND KELLER)

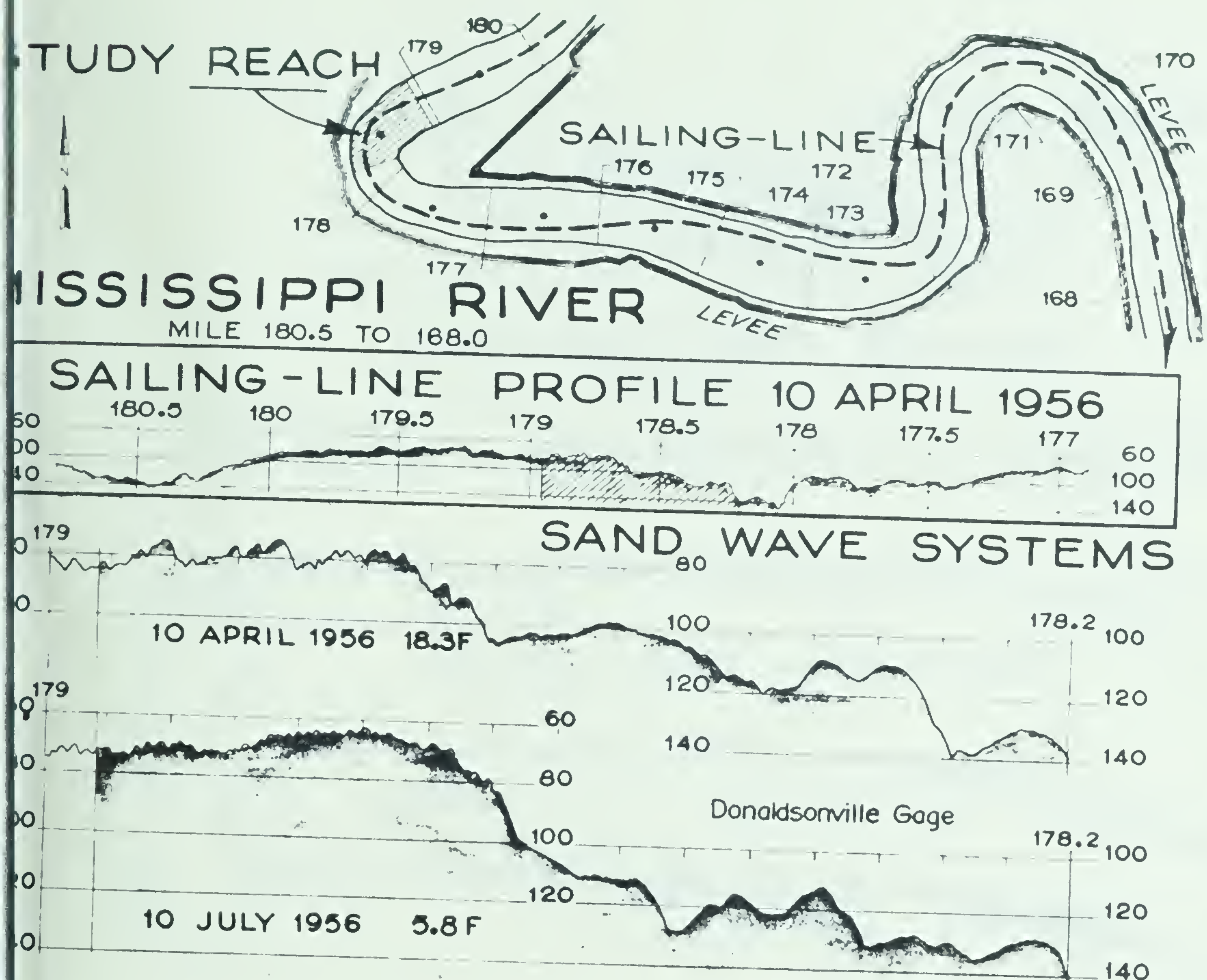


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FIG 11 (AFTER CAREY AND KELLER)

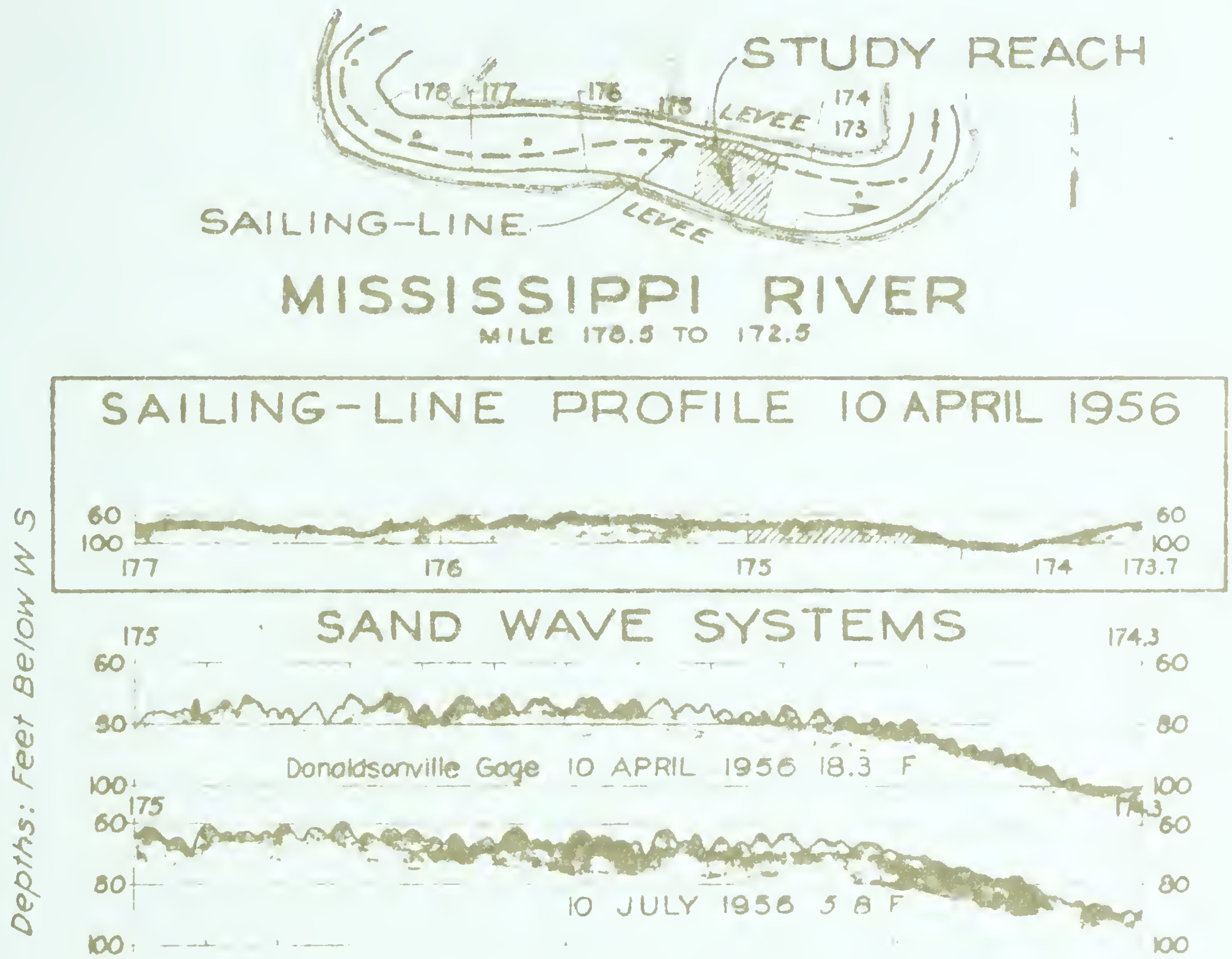

FIG 12 (AFTER CAREY & KELLER)

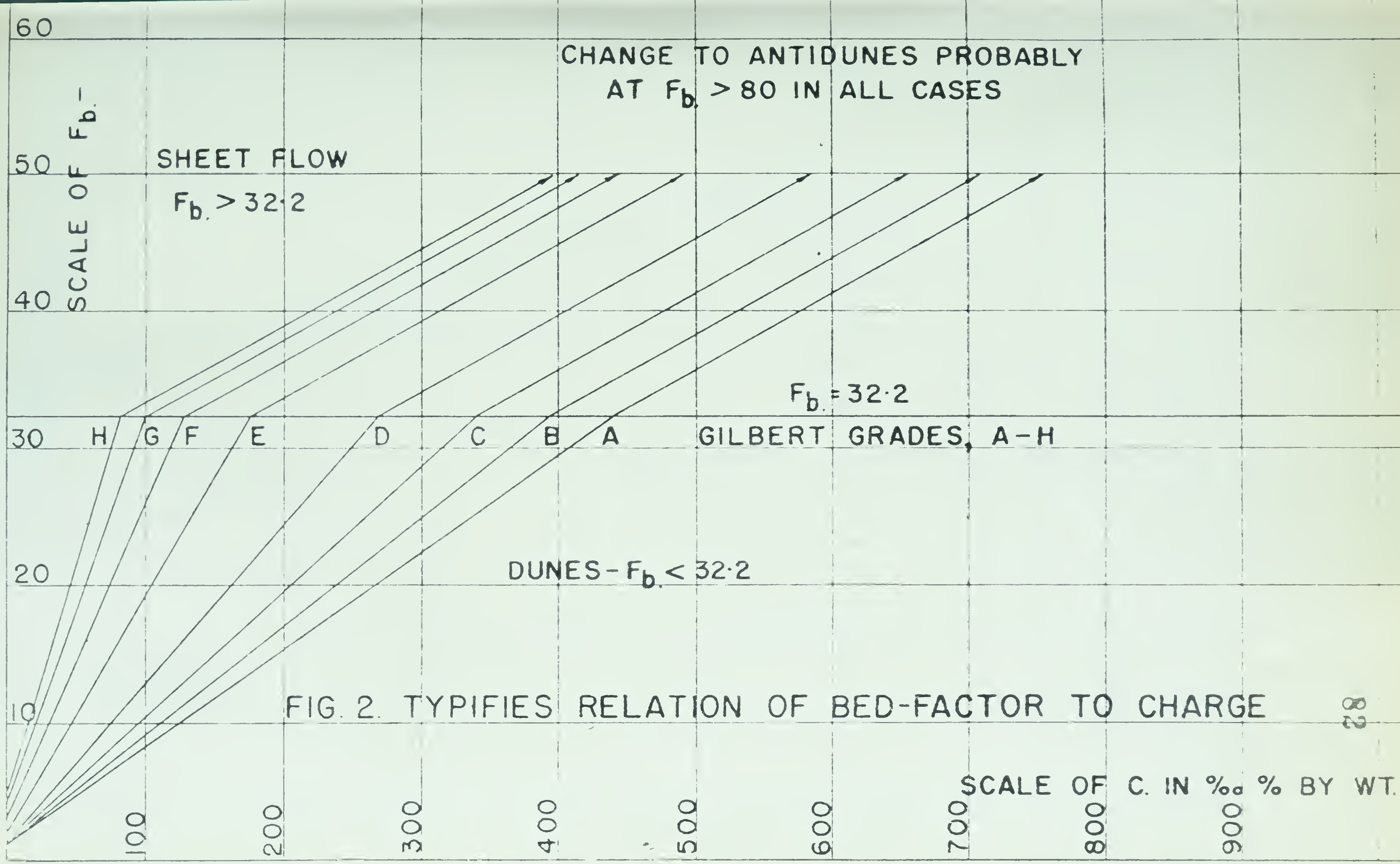

FIG. 2. TYPIFIES RELATION OF BED-FACTOR TO CHARGE

FIG. 13 (AFTER BLENCH & ERB

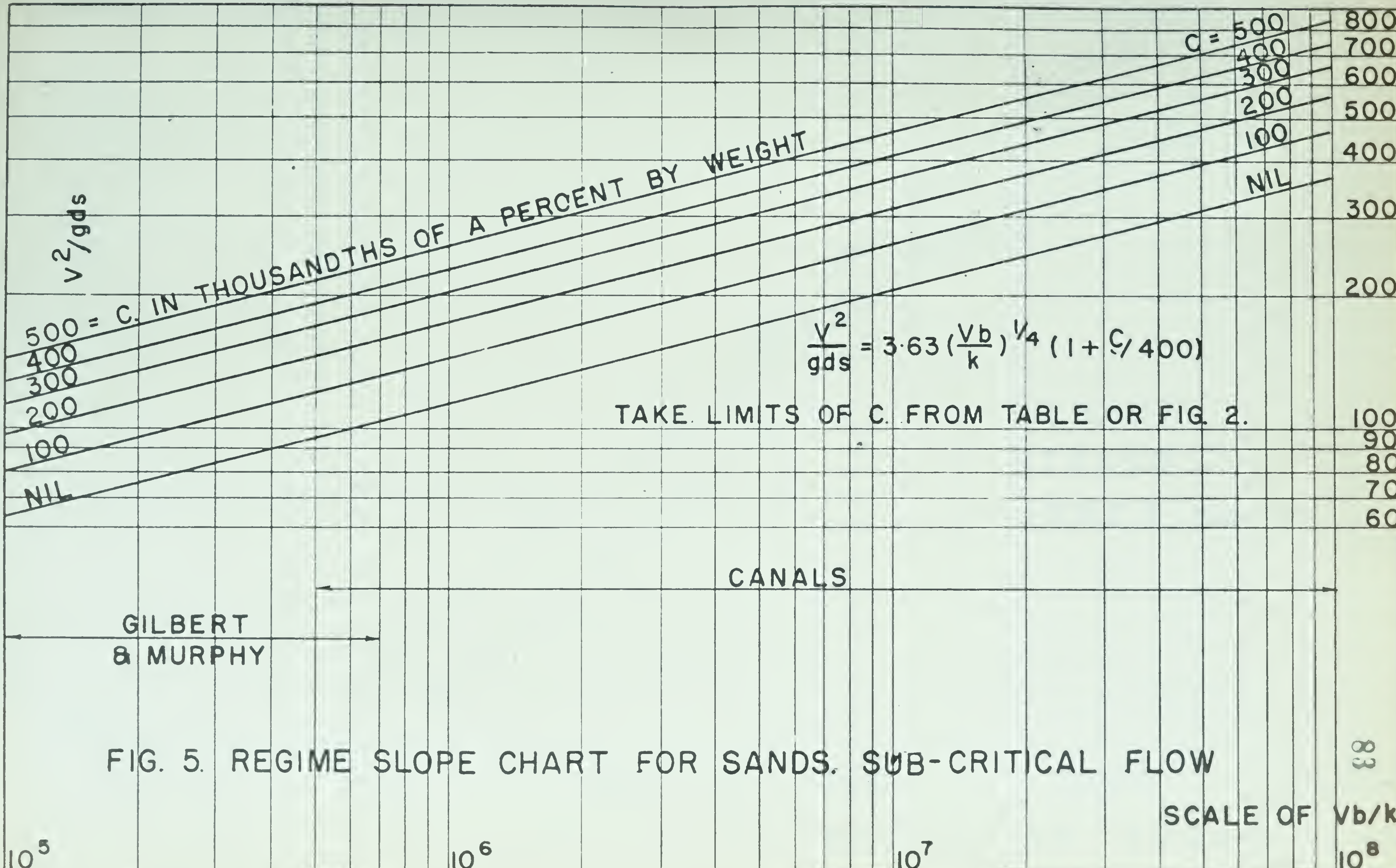

FIG. 5. REGIME SLOPE CHART FOR SANDS. SUB-CRITICAL FLOW

83

FIG.(14 AFTER BLENCH & ERB)

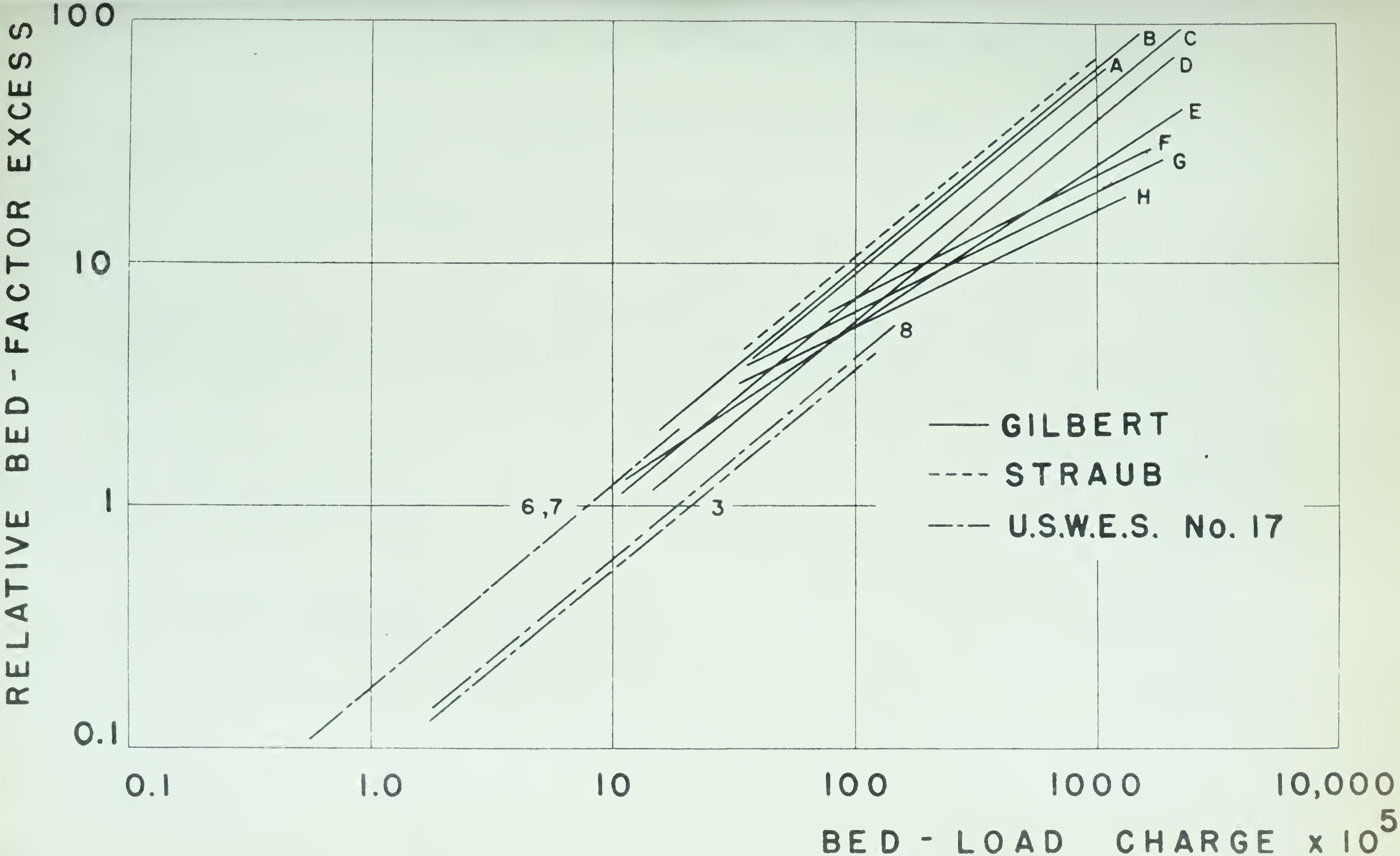

FIG. 15 (AFTER BLENCH & ERB)

FIGURE 5. VARIATION OF KING'S COEFFICIENT WITH SEDIMENT CHARGE

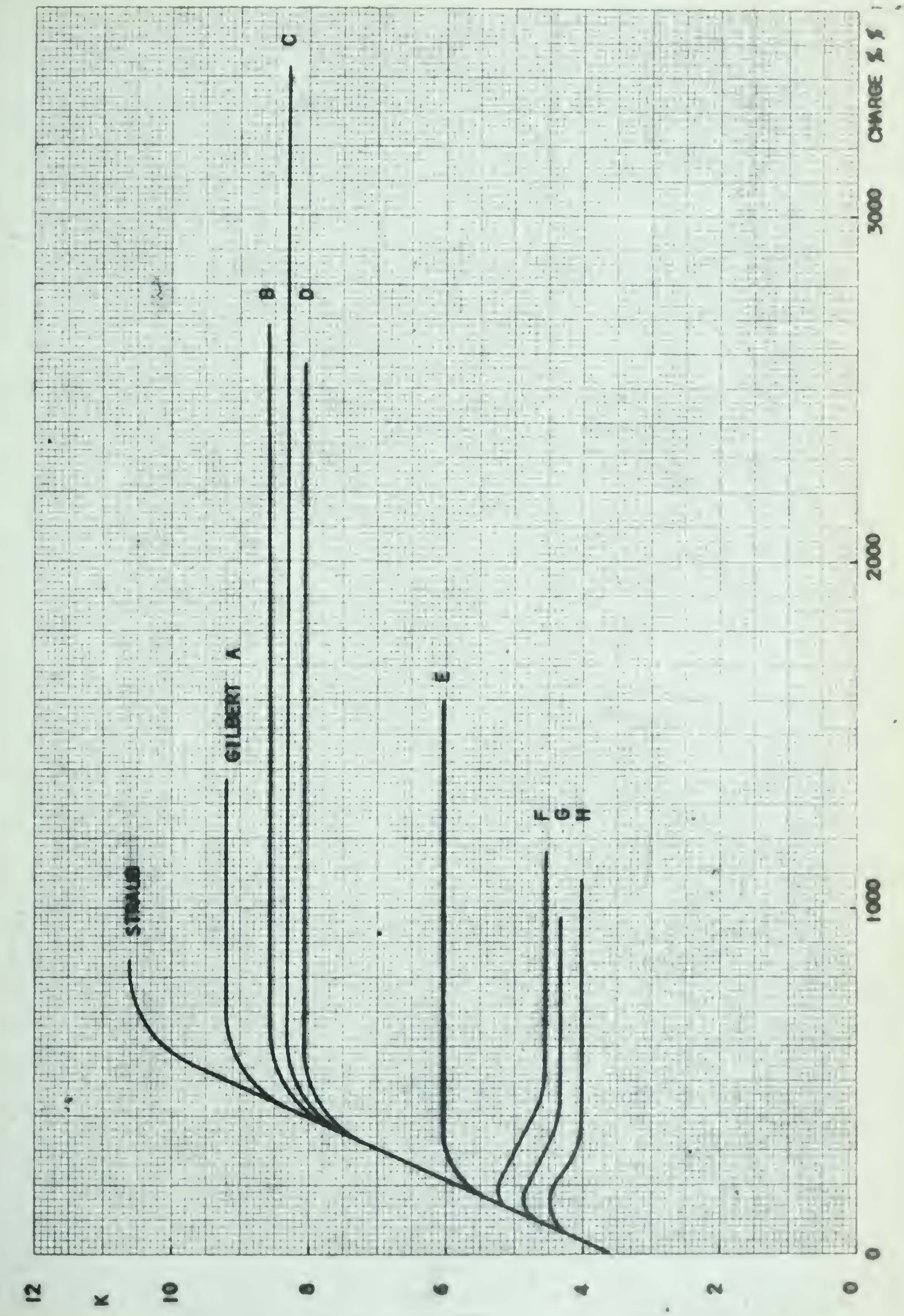

FIG. 16 (AFTER BLENCH & ERB)

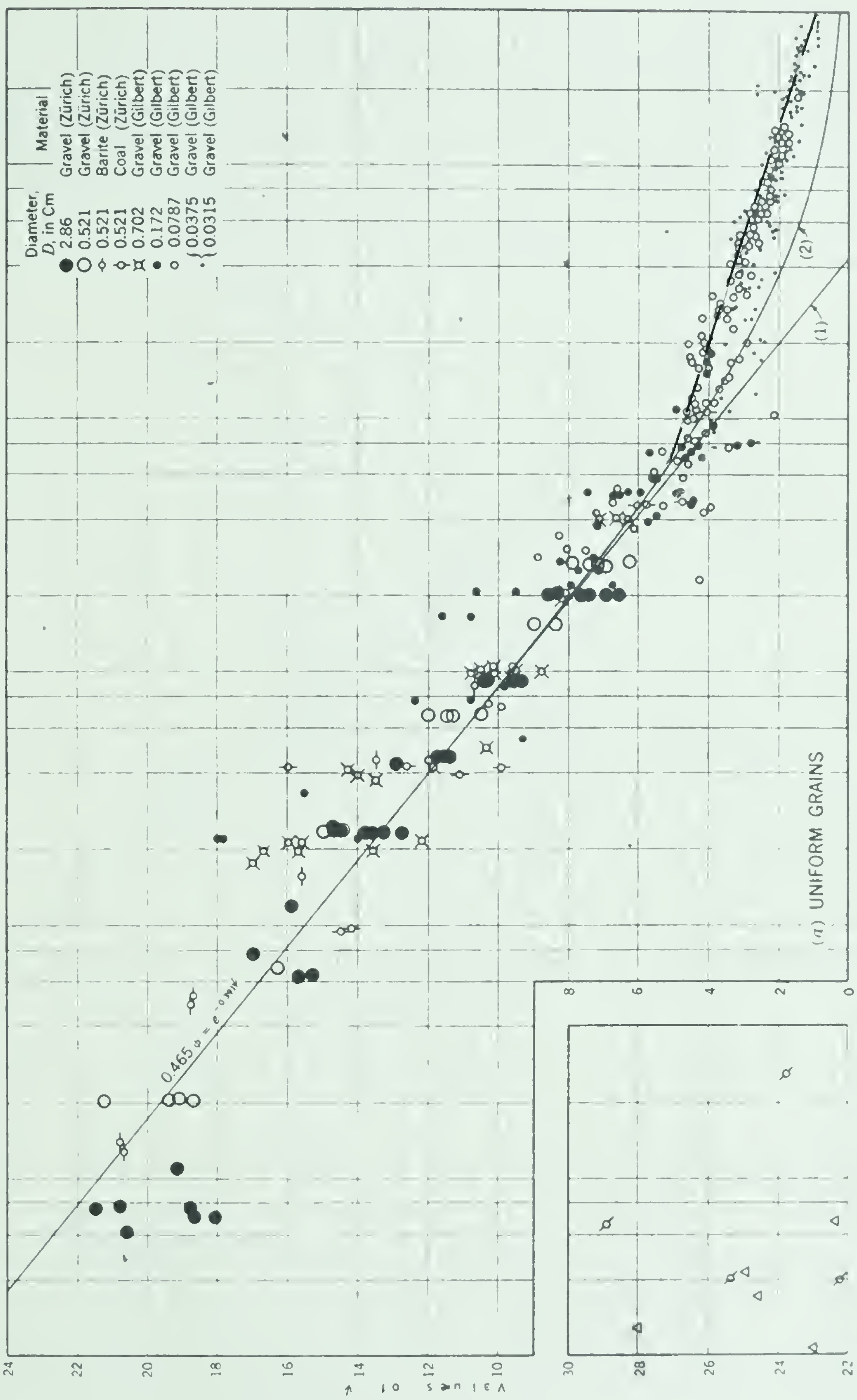

FIG. 17 (AFTER EINSTEIN)

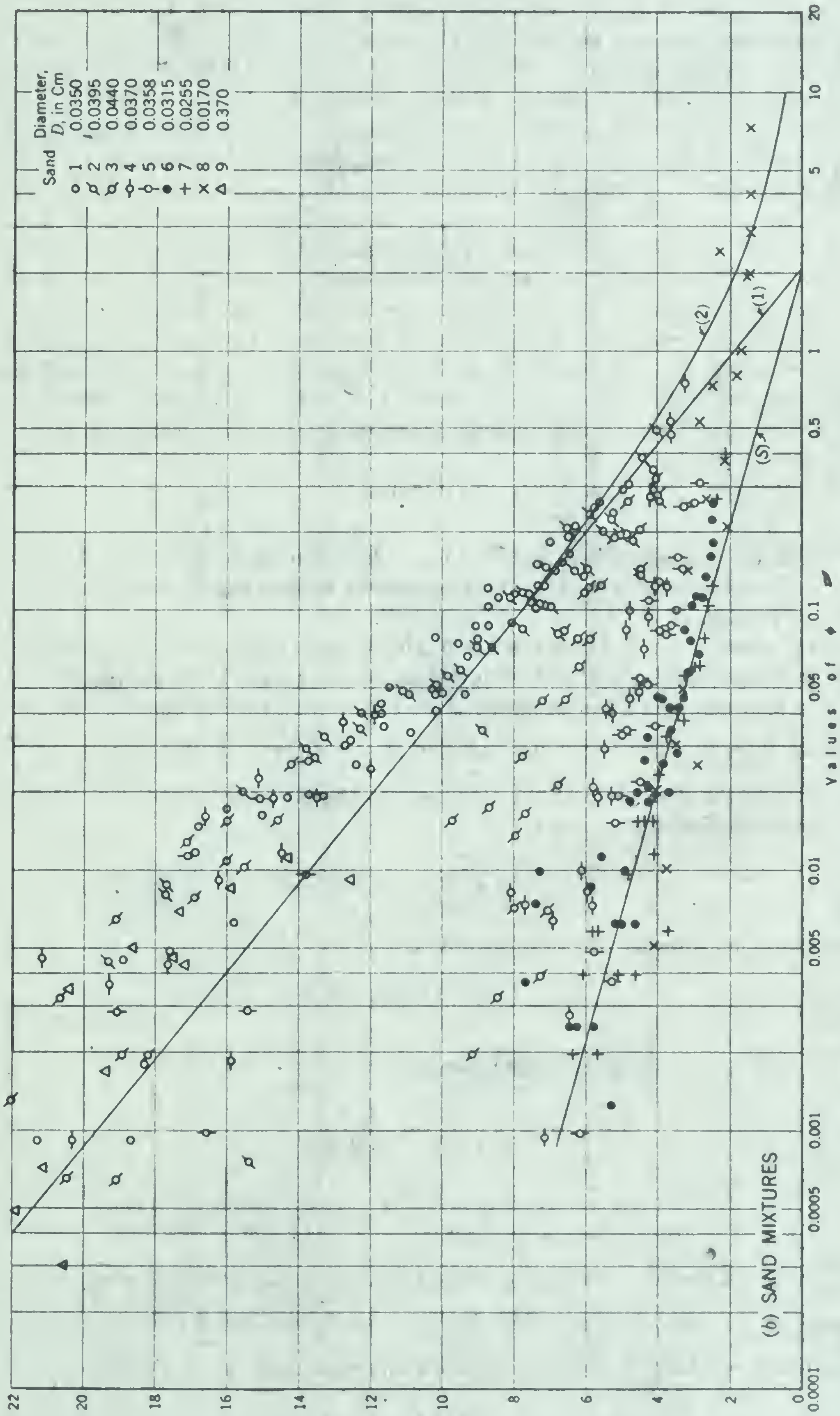

Fig. 3.—Bed-Load Experiments Showing the Relation Between φ and ψ

FIG 18.(AFTER EINSTEIN)

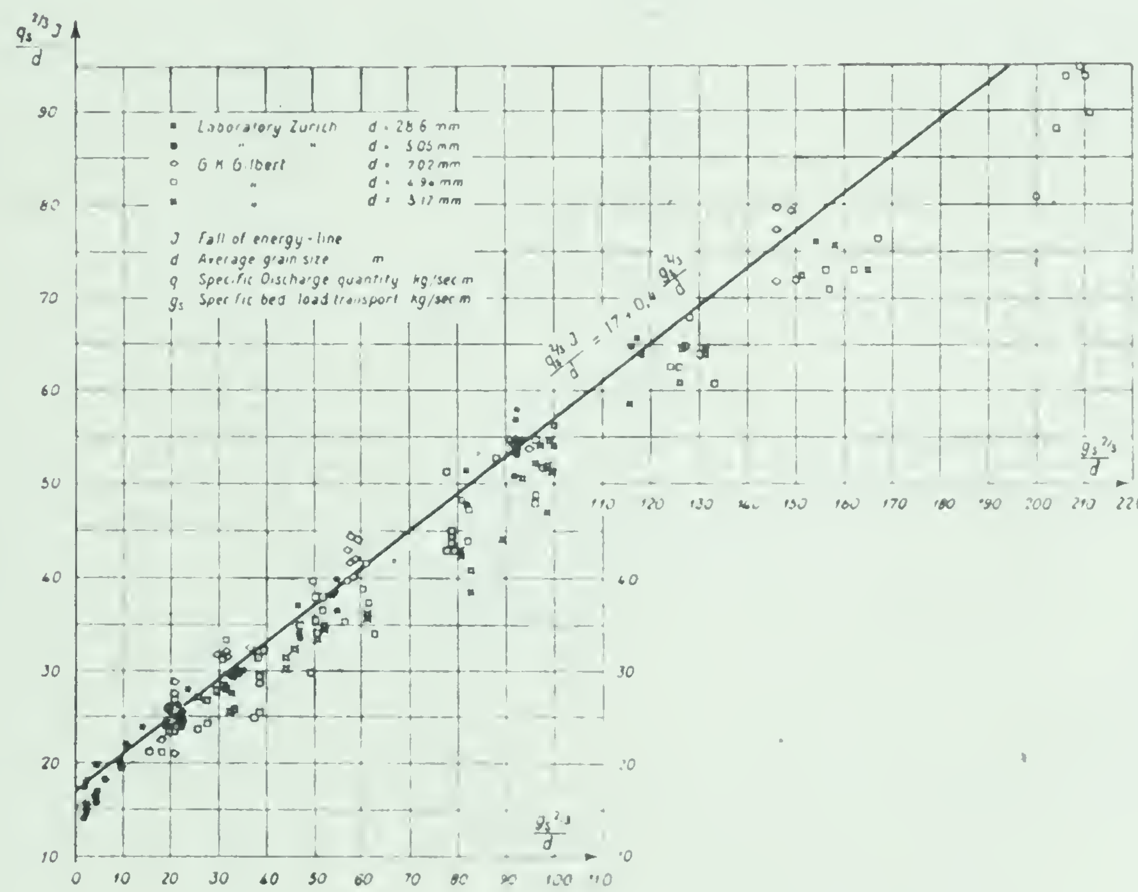

FIG 19 (MEYER-PETER).

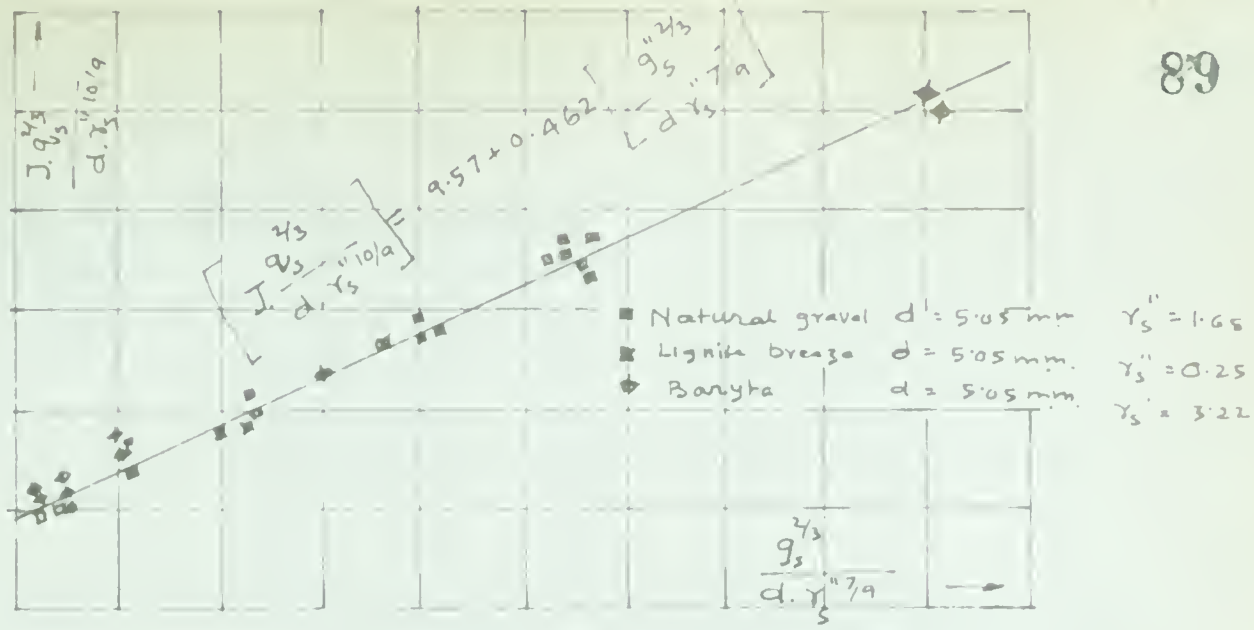

FIG - 20. $\frac{q_s^{2/3} J}{d \gamma_s''^{10/9}}$ Against $\frac{g_s^{2/3}}{d \gamma_s''^{7/9}}$

AFTER MEYER-PETER

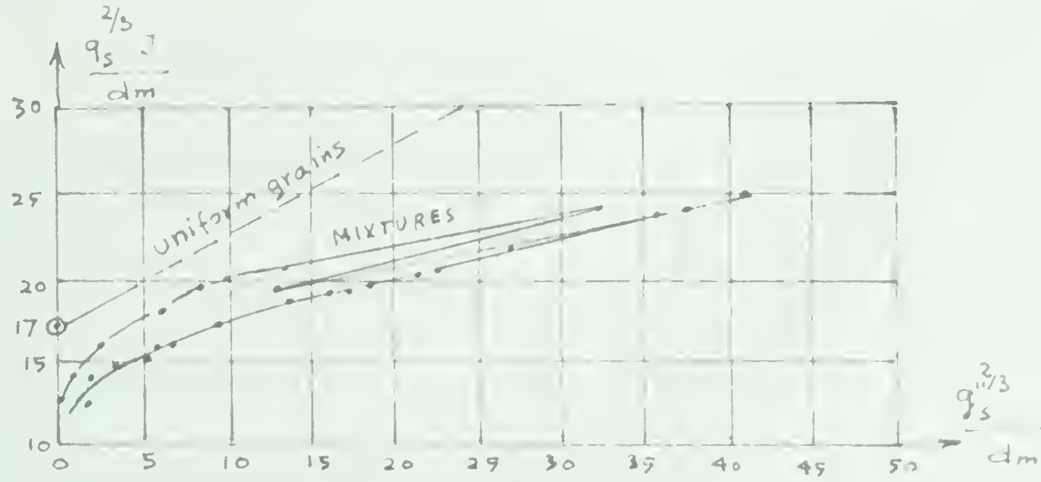

FIG 21 $\frac{q_s^{2/3}}{d_m}$ AGAINST $\frac{g_s''^{2/3}}{d_m}$

(AFTER MEYER-PETER)

J = Fall of energy Line

d = Average grain size

q_s = Specific discharge quantity kg/sec m

g_s = Specific bed load transport kg/sec. m.

g_s'' = Specific bed load transport weighed under water.

γ_s'' = Specific gravity of the bed load weighed under water

EXPTS. WITH STONES AND BLOCKS

CONDITIONS FOR INITIAL MOVEMENT OF STONES IN SINGLE LAYER & ISOLATED CUBICAL BLOCKS

	CUBICAL BLOCKS		STONES	
	SIZE OF BLOCKS IN FEET.	SP. GR.	MEDIAN DIA. IN FEET.	SP. GR.
×	·043	2·16	·0141	2·9
+	,,	2·39	·0229	,,
⊙	,,	3·61	·0303	,,
□	·083	2·44	·0273	,,
△	,,	2·28	·0303	,,
◬	,,	2·14	·0369	,,

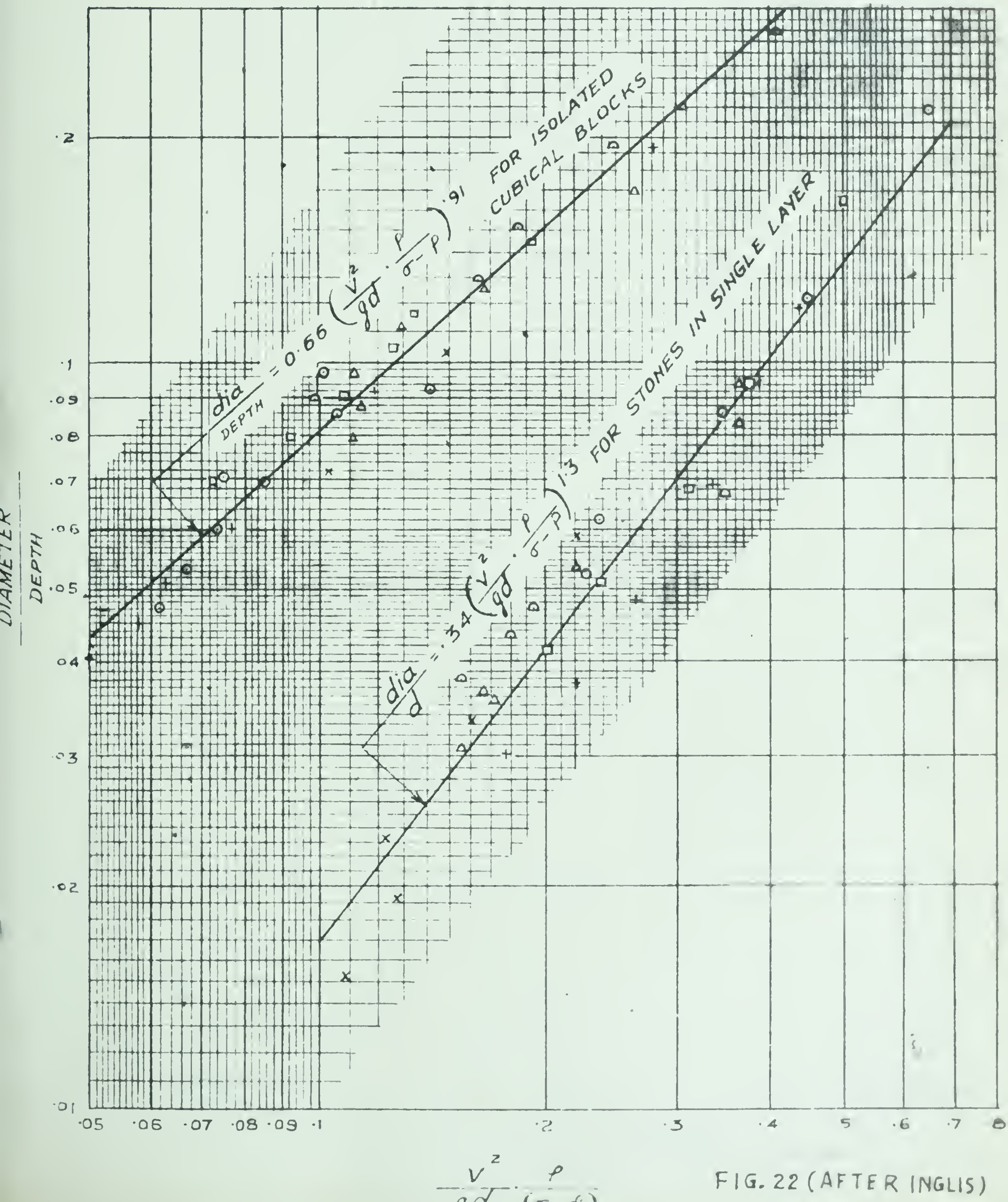

FIG. 22 (AFTER INGLIS)

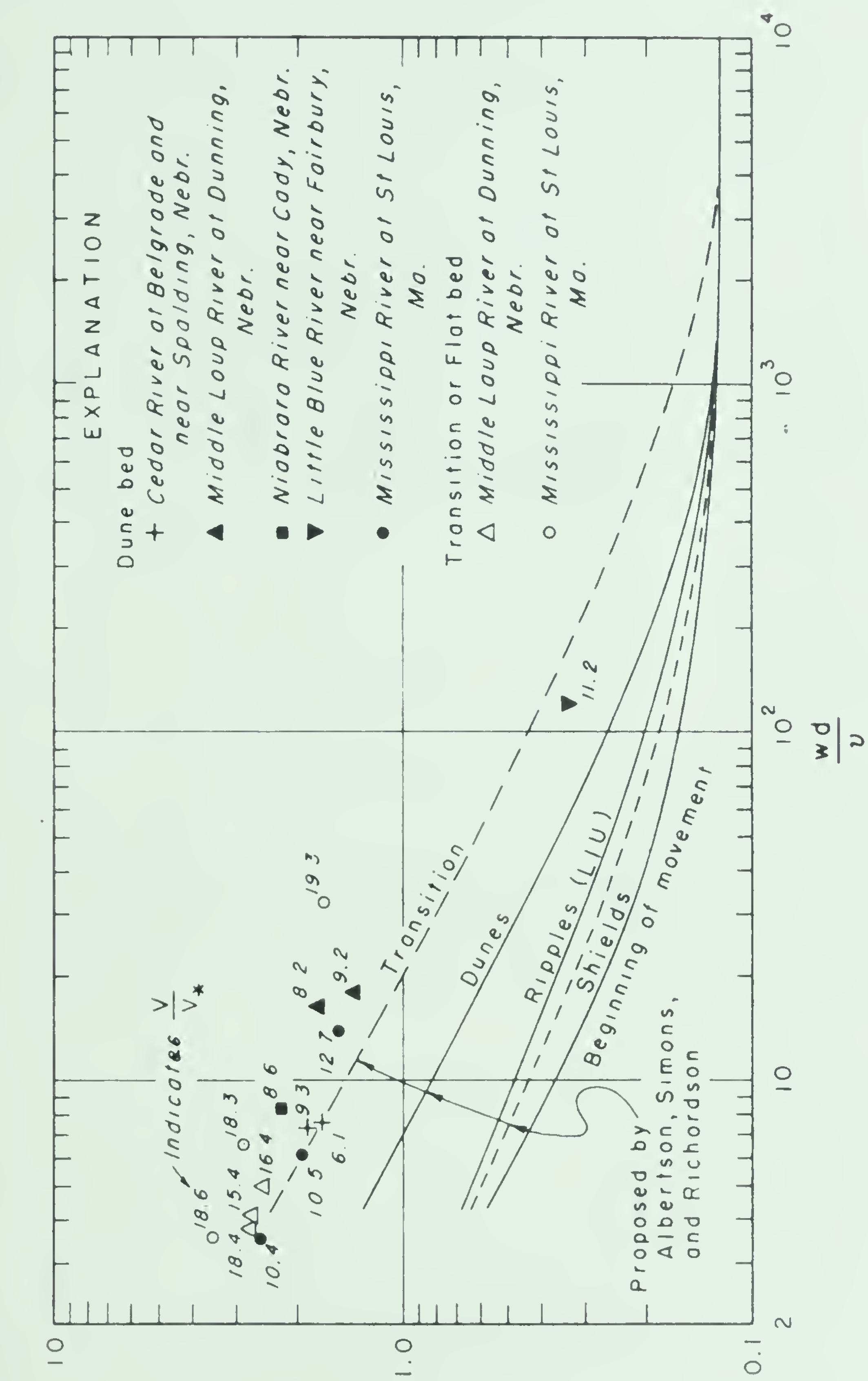

FIG. 1.—CLASSIFICATION OF THE CONFIGURATION OF ALLUVIAL BED

FIG. 23 (AFTER LIU & HWANG)

ASCE LIU 1197-21

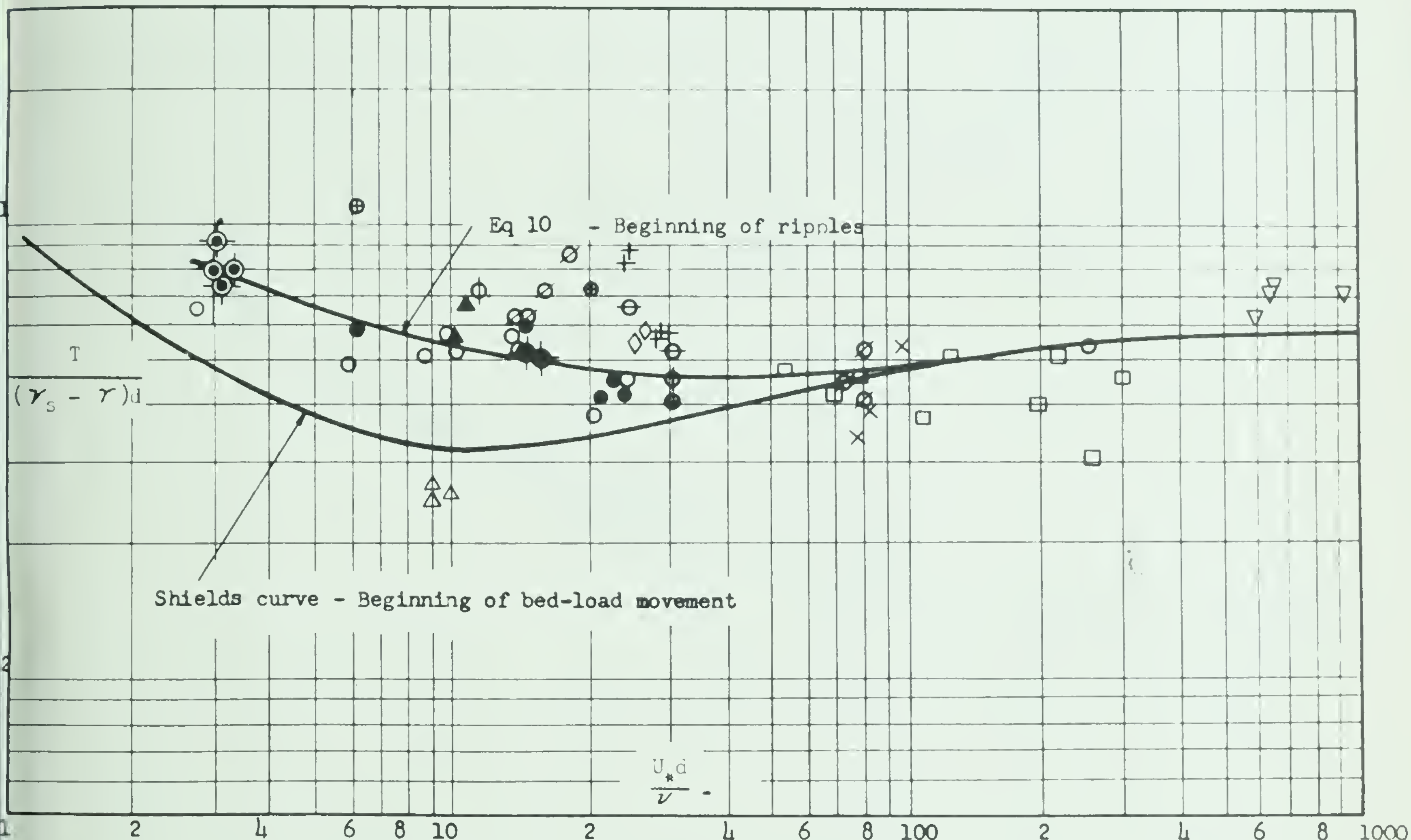

Fig. 11 - Data of Ripple Formation Plotted in terms of $T/(\gamma_s - \gamma)d$ versus $\frac{U_* d}{\nu}$

FIG 24. (AFTER LIU)

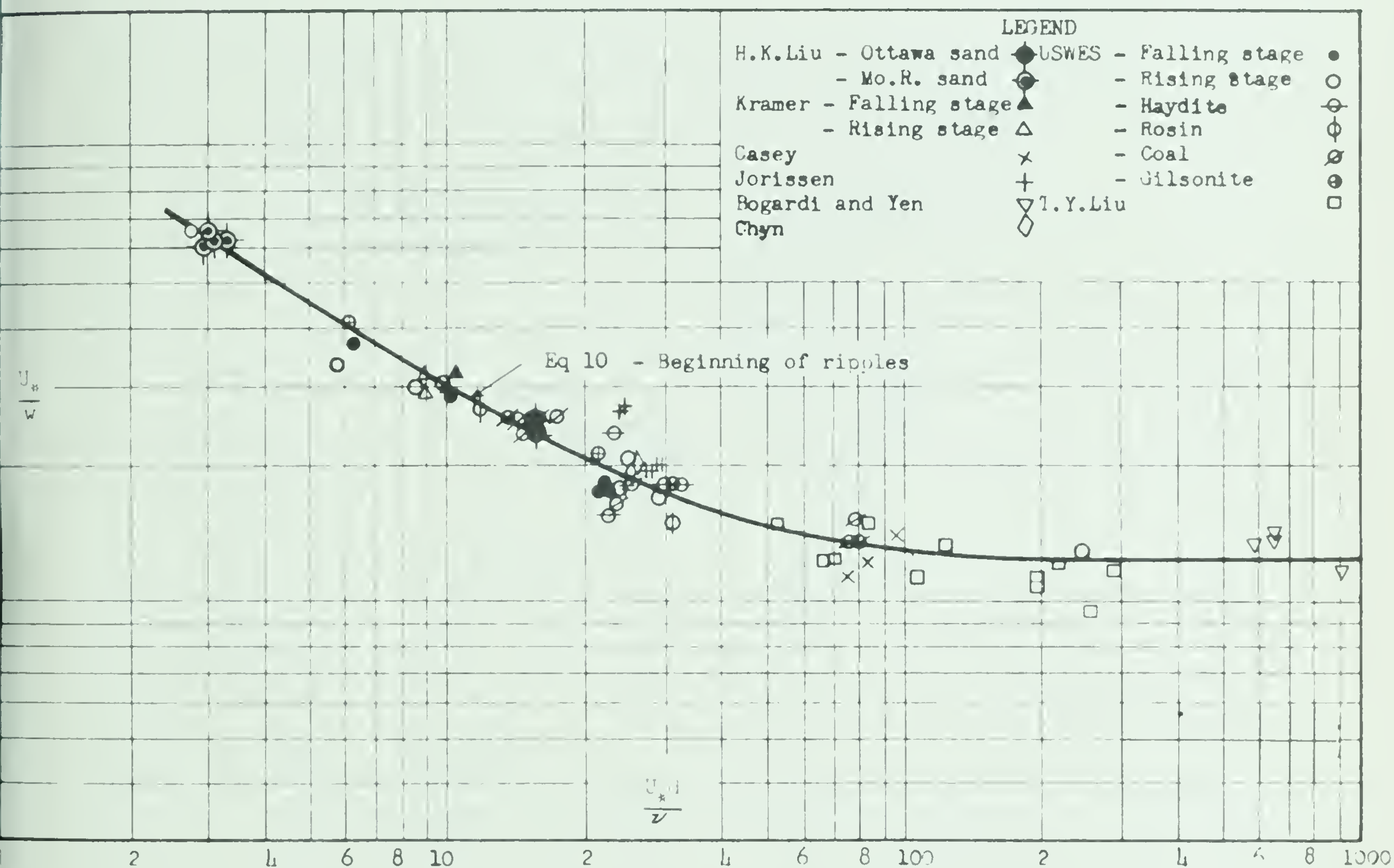

Fig. 9 - Criterion of Ripple Formation as a Function of $\frac{U_*}{w}$ and $\frac{U_* d}{\nu}$.

FIG 25.(AFTER LIU)

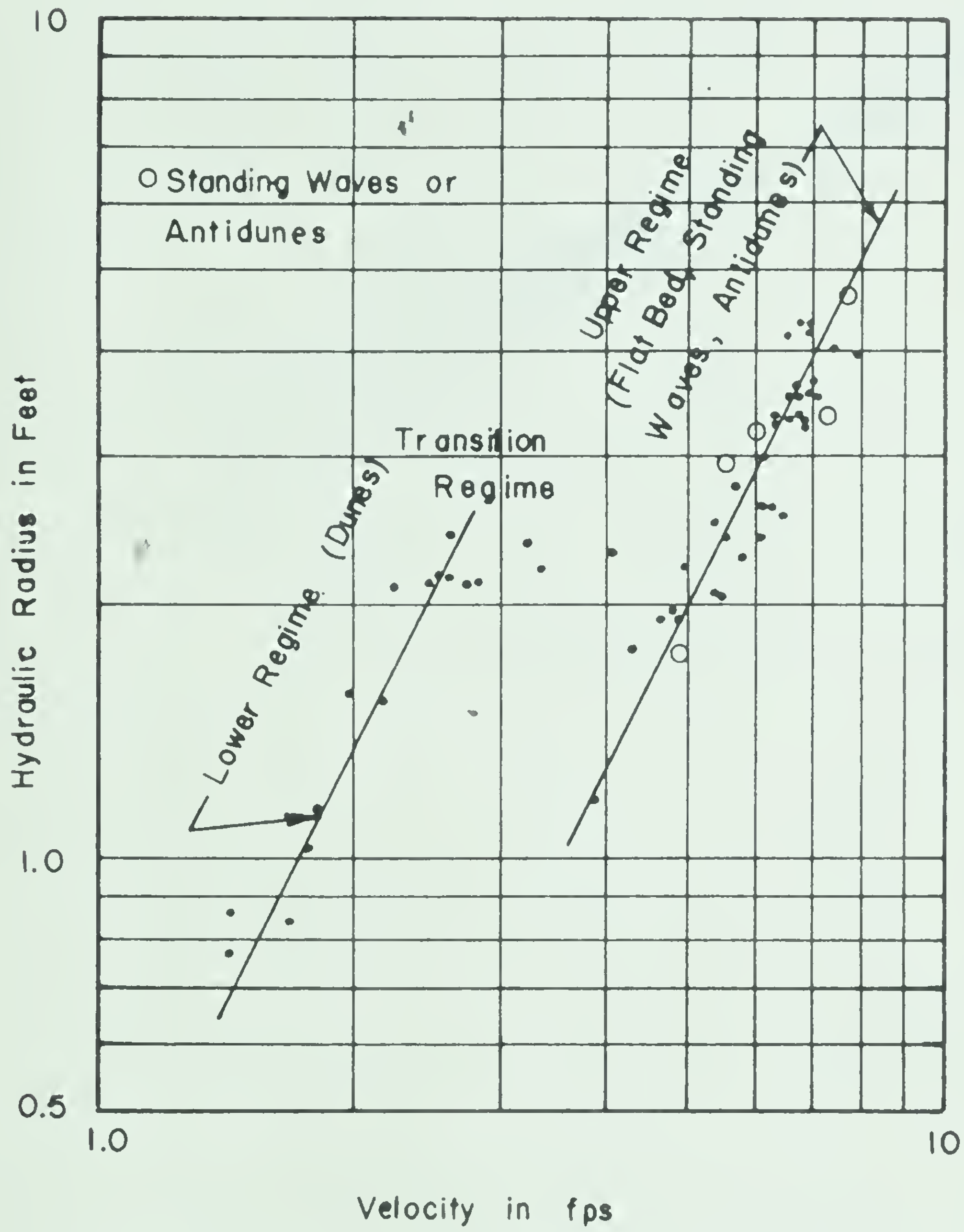

FIG. A.—RELATION OF HYDRAULIC RADIUS TO VELOCITY FOR RIO GRANDE NEAR BERNALILLO, NEW MEXICO

FIG 26 (AFTER CULBERTSON)

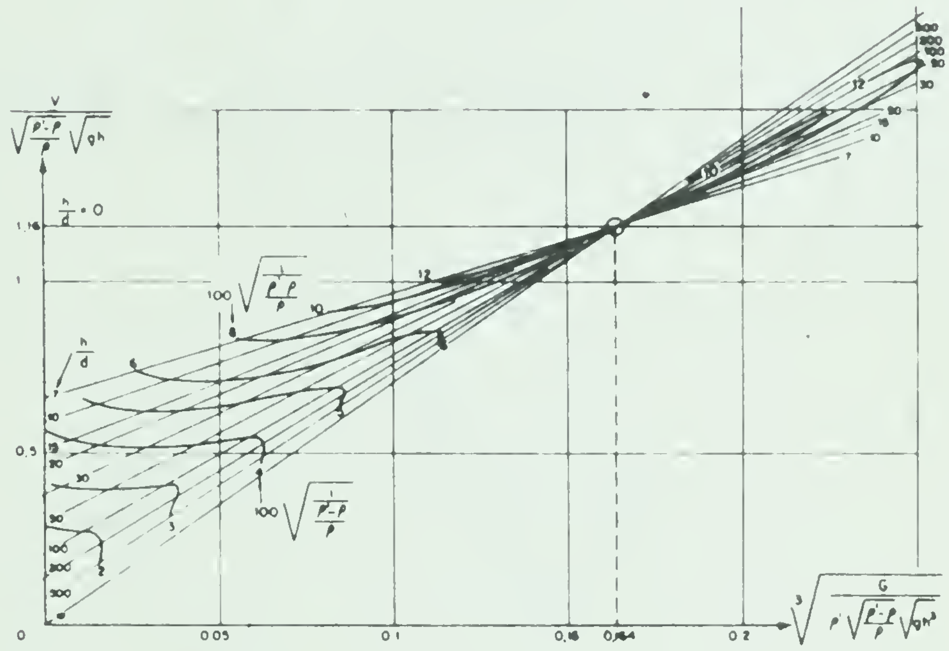

FIG. 1.—DATA FOR STRAIGHT ALLUVIAL CHANNELS

FIG. 27 (AFTER ROTTNER)

FRASER RIVER
BED SAND SIZE
(PLOTTED AGAINST DEPTH)

SAMPLING POINT	A_1	A_2	A_3	B_1	B_2	B_3	D_1	D_2	D_3	C_1	C_2
MEDIAN DIAM (MM)	0·35	·31	·25	·294	·33	·37	·32	·33	·385	·22	·22
DEPTH (FT)	8·1	11·5	22	11	19	25·5	18	17	27	16	18
REMARKS	← PARENT			← WOOD WARD REACH						← LADNER →	

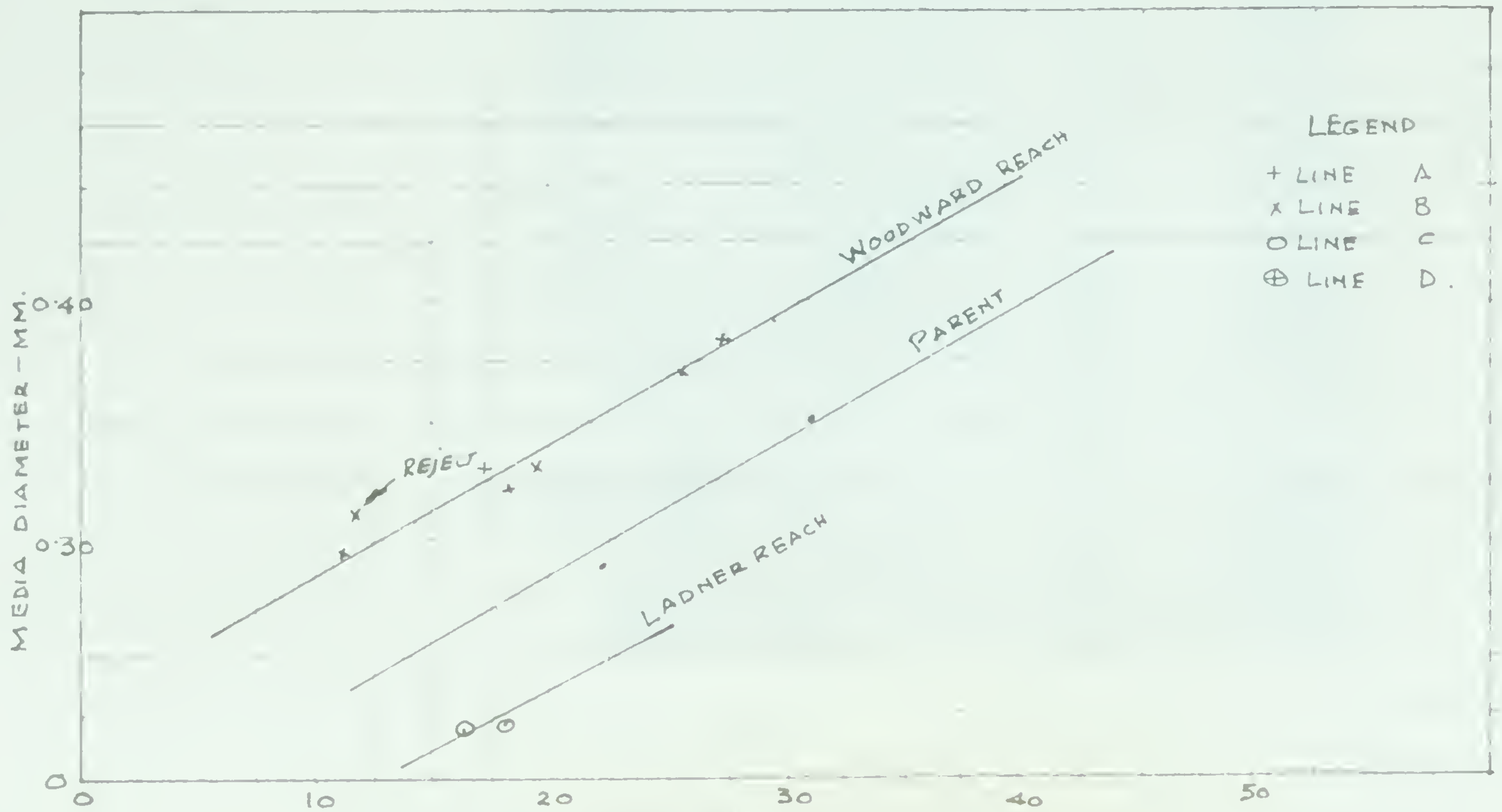

FIG 28 · DEPTH OF BED BELOW L.L.W – FEET.
(AFTER BLENCH)

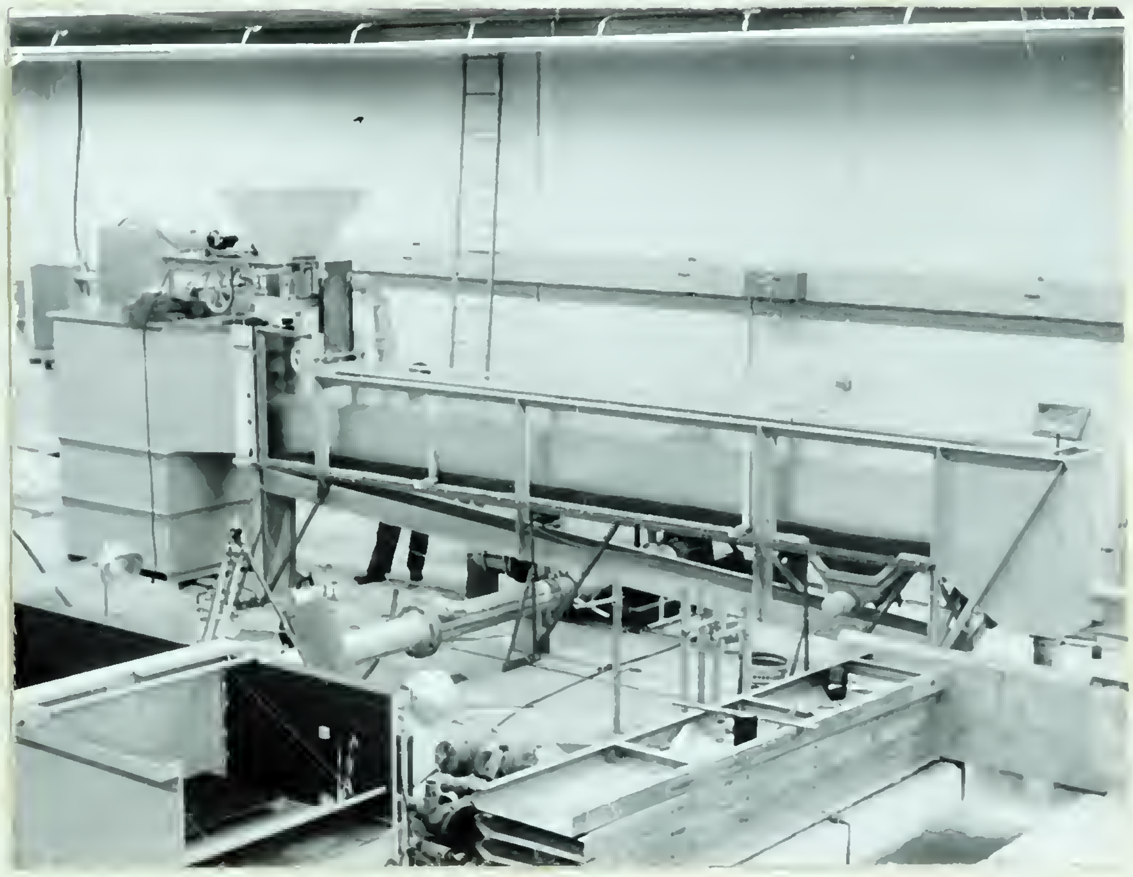

FIG.29 12" GLASS WALLED FLUME.

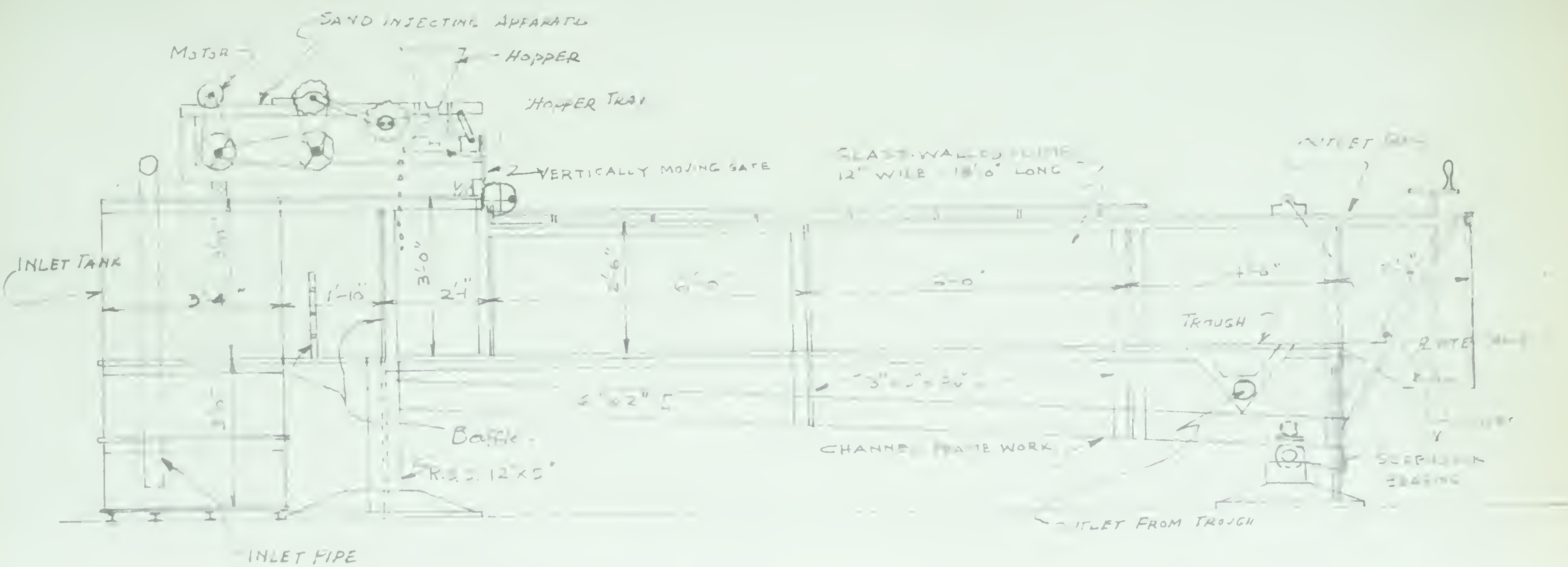

FIG 30 SKETCH OF 12" WIDE GLASS FLUME.
(SCALE 3' TO AN INCH)

FIG 31: MECHANICAL ANALYSIS OF GRAVEL (1·70MM)
(BEFORE EXPERIMENT)

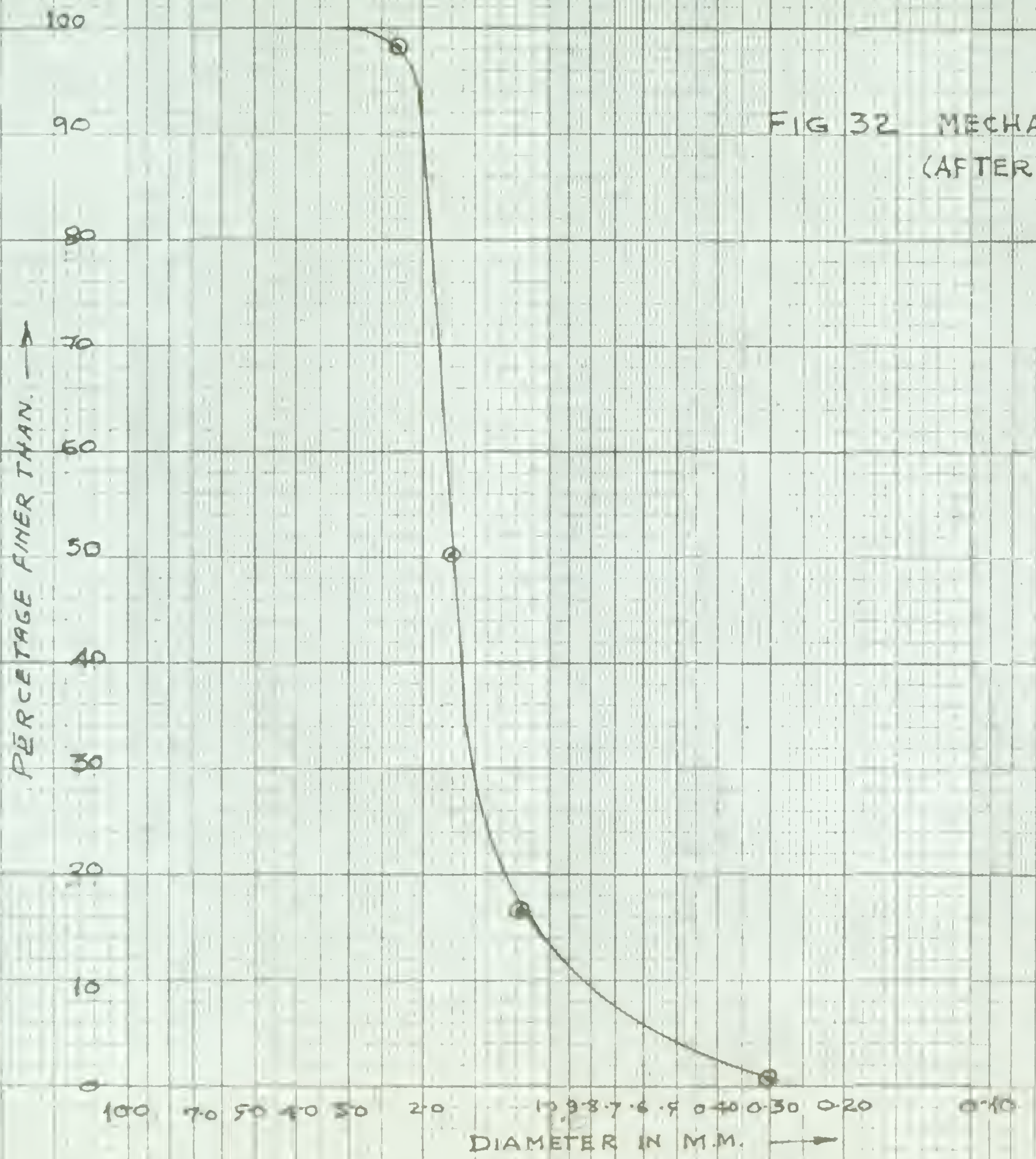

FIG 32 MECHANICAL ANALYSIS OF GRAVEL (1·70MM)
(AFTER EXPERIMENT.)

(SKETCHES. NOT TO SCALE)

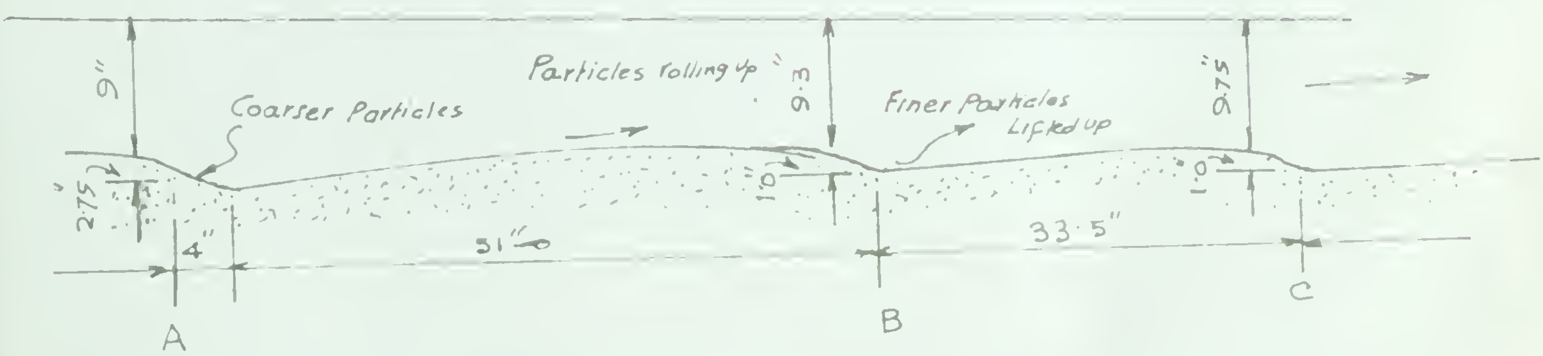

FIG 33. DUNE PROFILE MOVING - RUN 3

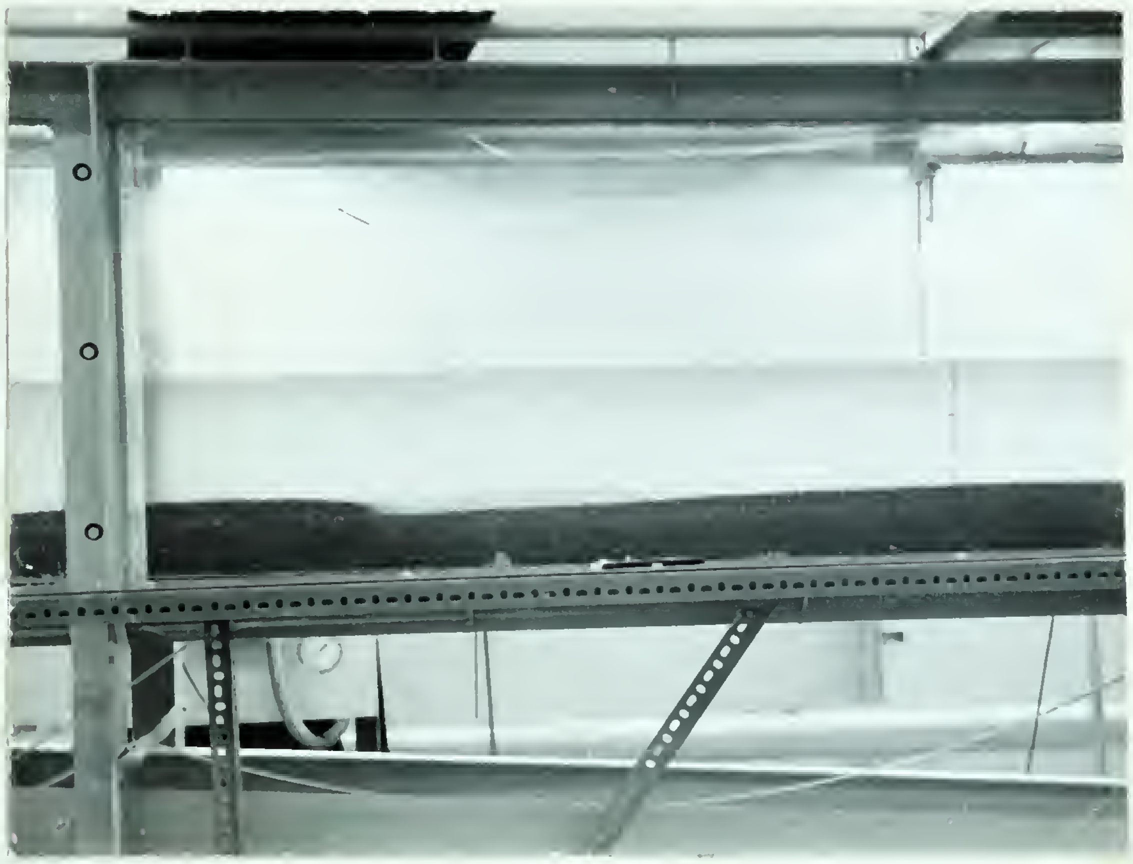

FIG.34 A LONG BED WAVE OR DUNE.

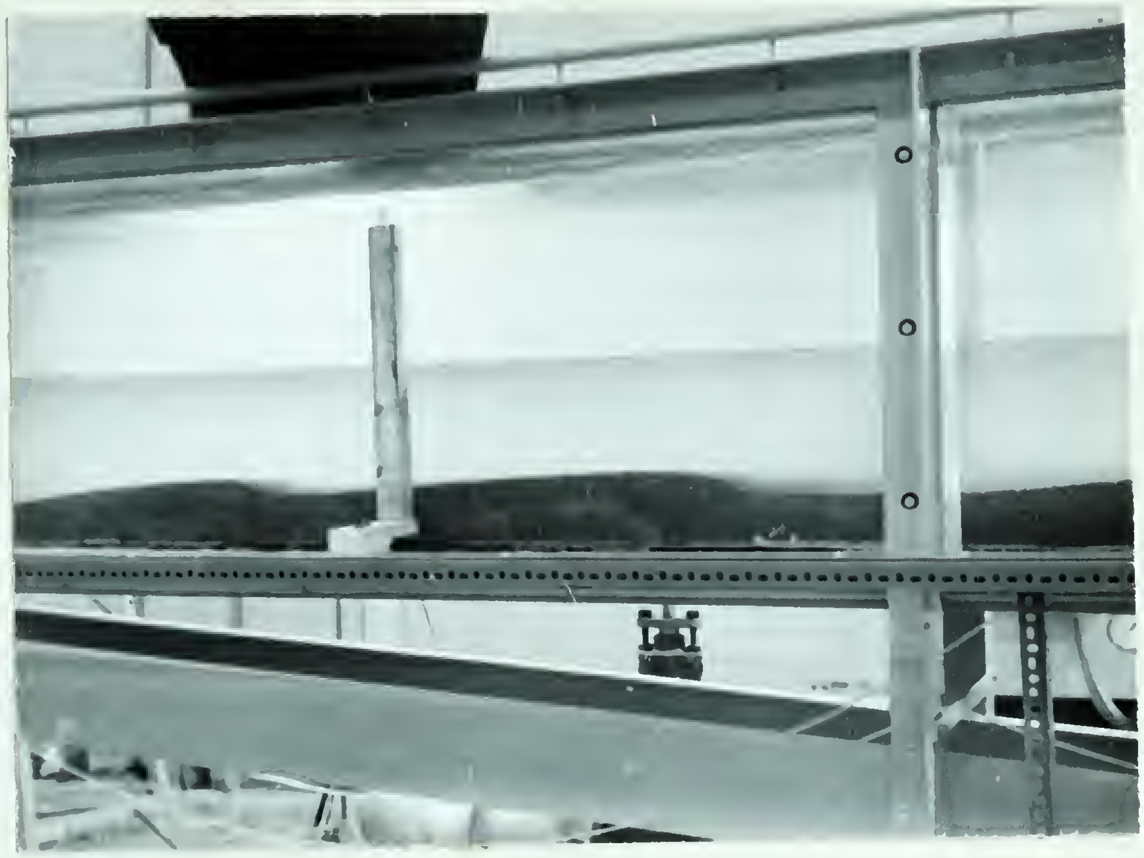

FIG 35 2 DUNES MOVING

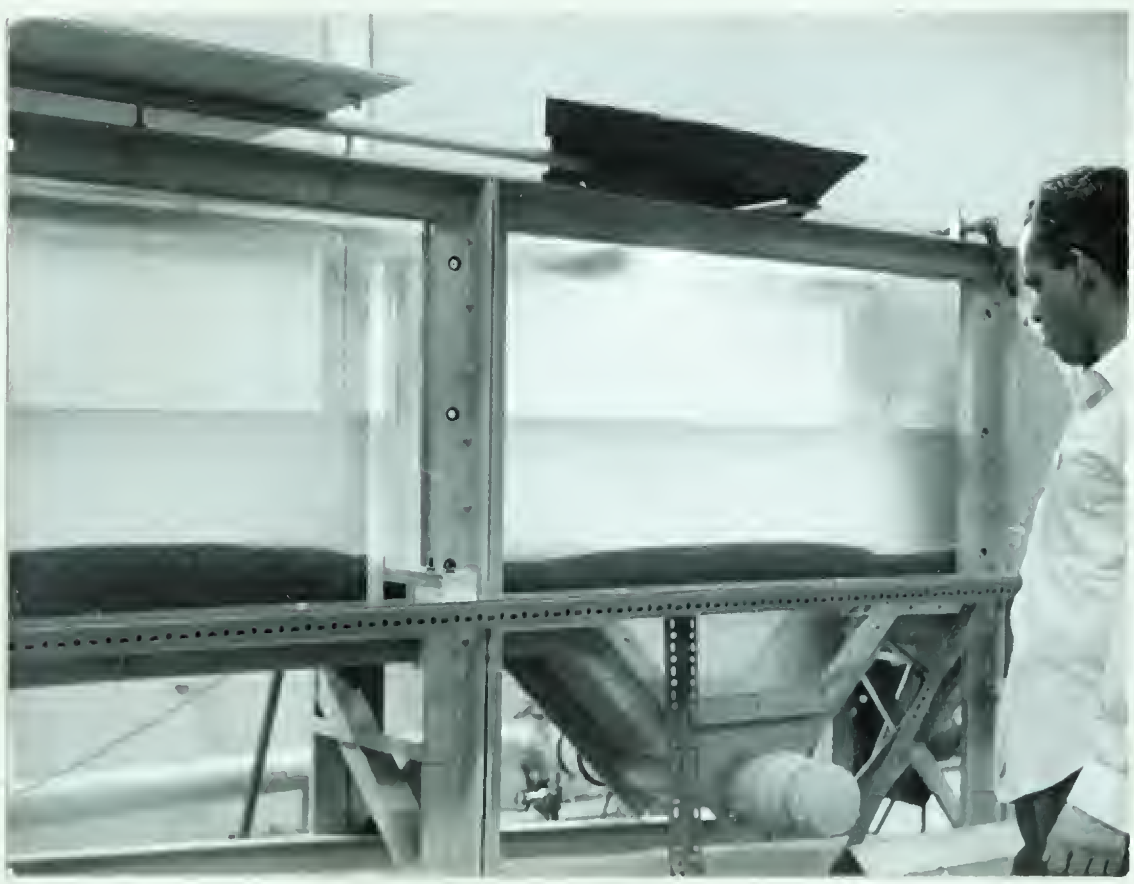

FIG 36. EXCESSIVE SCOUR IN FRONT OF FIRST DUNE.

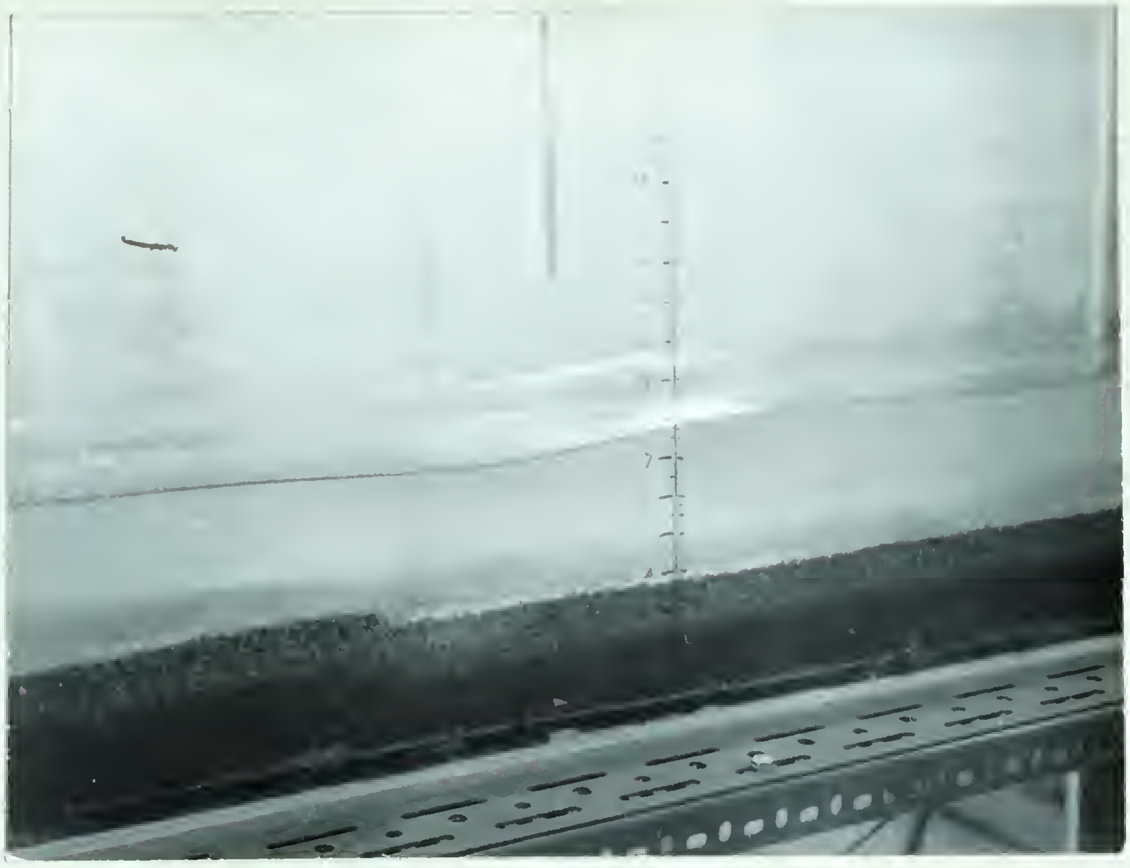

FIG 37-a DUNE WITH WAVY SURFACE OF WATER.

FIG 37-b. DUNES WITH WAVY SURFACE OF WATER.

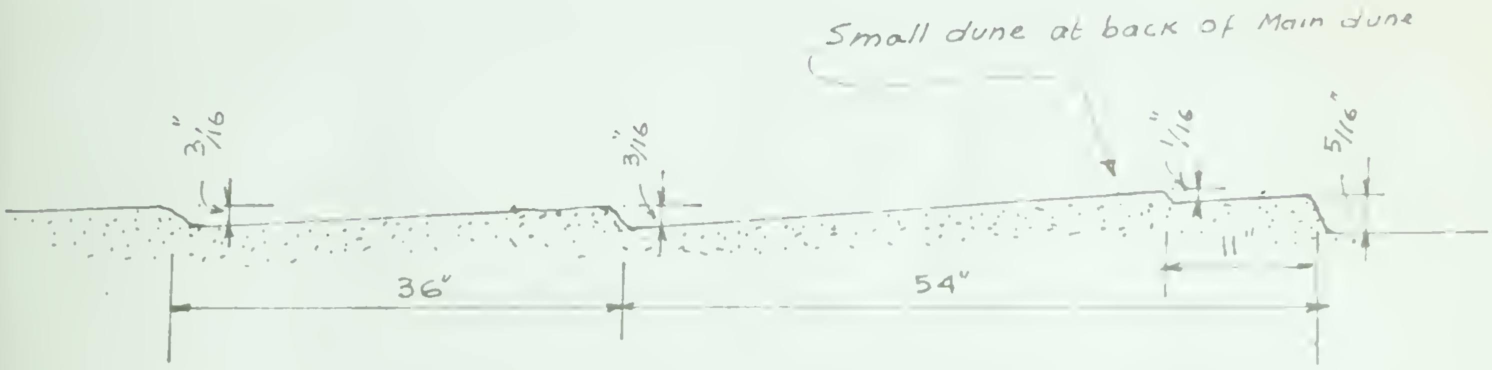

FIG. 40. DUNE PROFILE AFTER RUN 13.

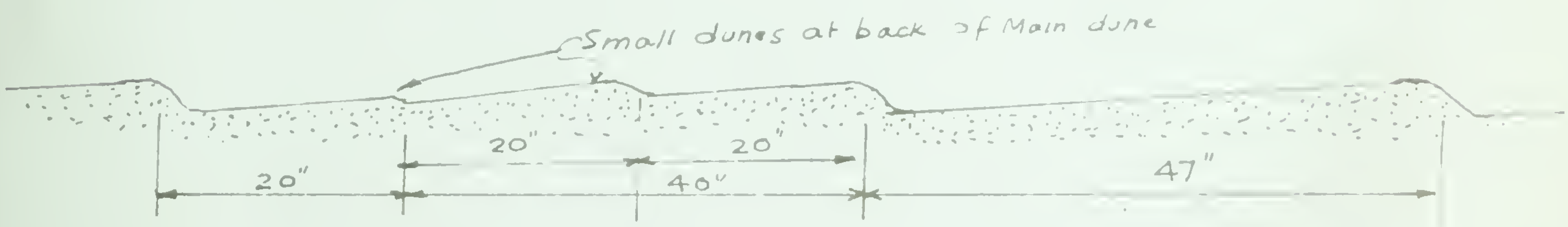

FIG 41. DUNE PROFILE RUN-14 (IN PROGRESS)

(SKETCHES NOT TO SCALE.)

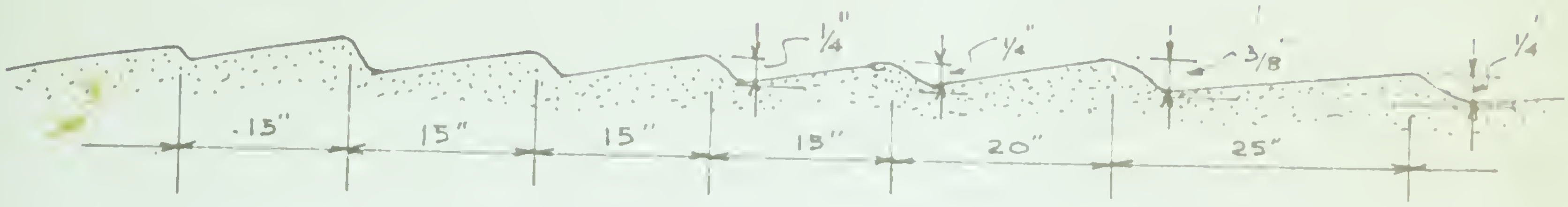

FIG 42 DUNE PROFILE AFTER RUN-15.

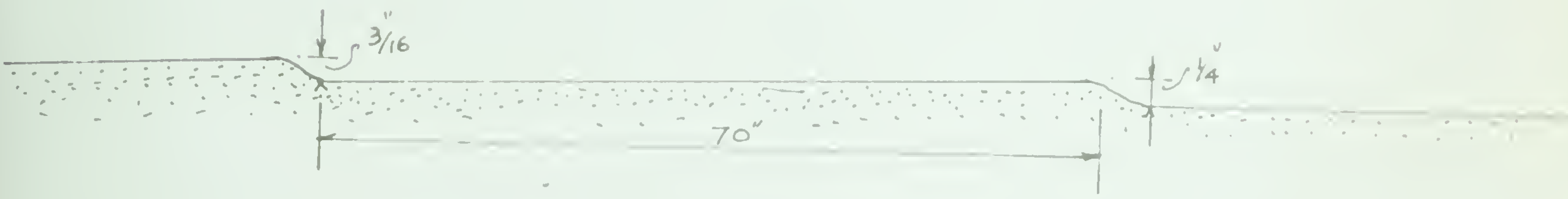

FIG. 43. DUNE PROFILE AFTER RUN 17

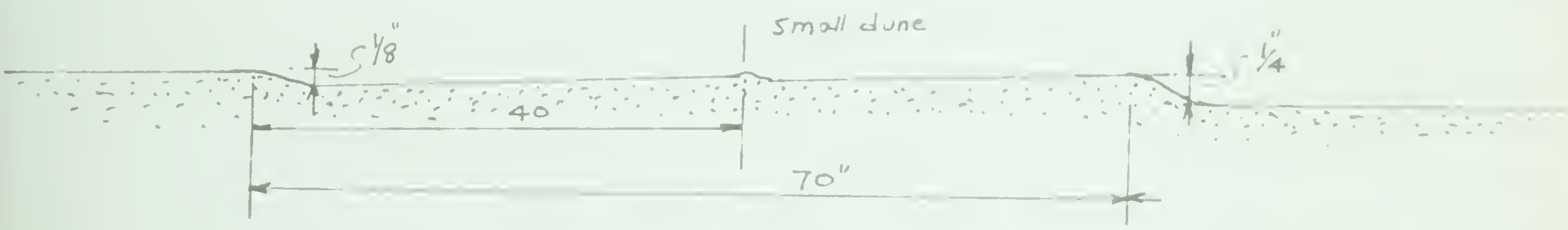

FIG 44. DUNE PROFILE AFTER RUN-21

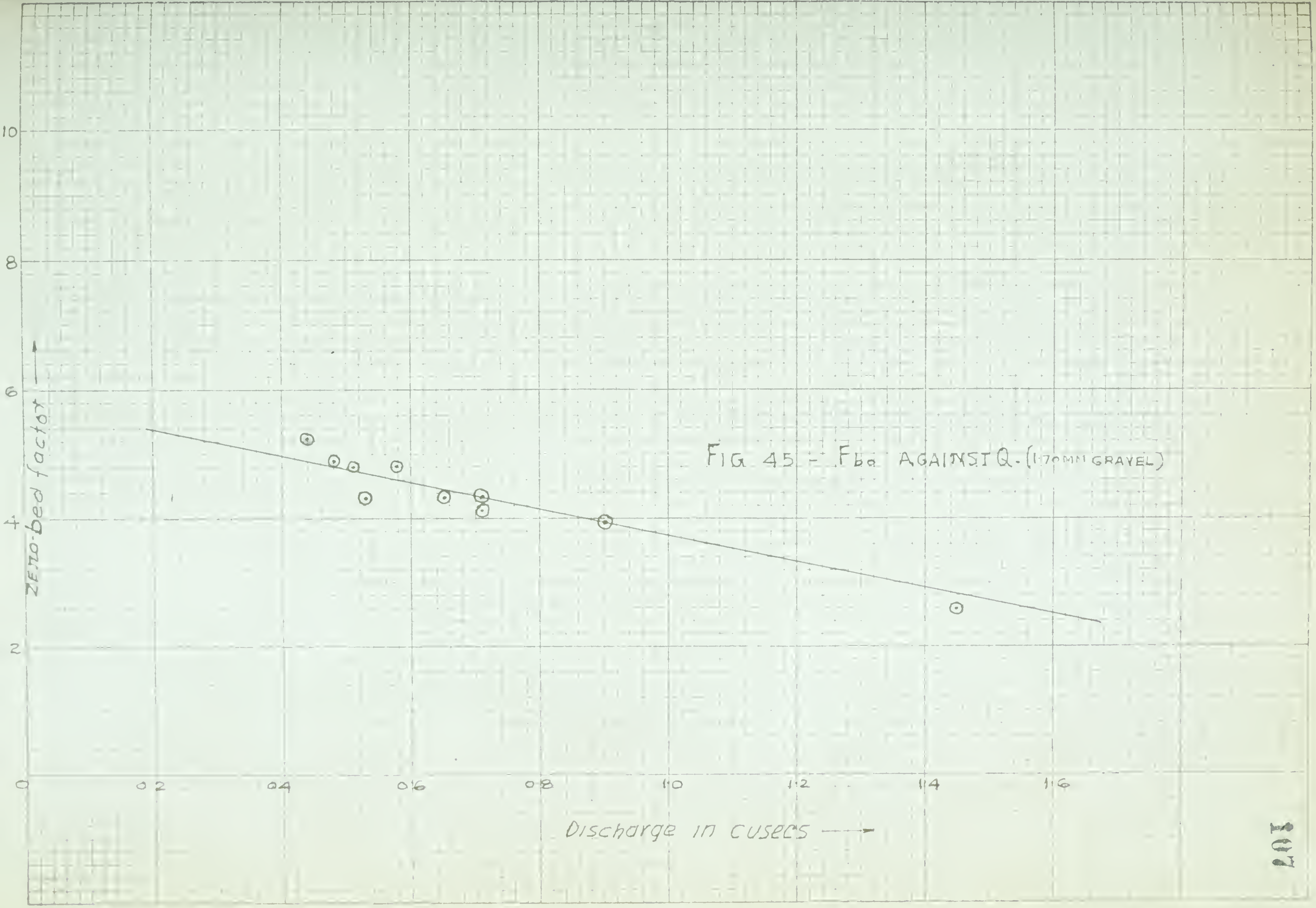

FIG 45 - F_{bo} AGAINST Q. (1.70MM GRAVEL)

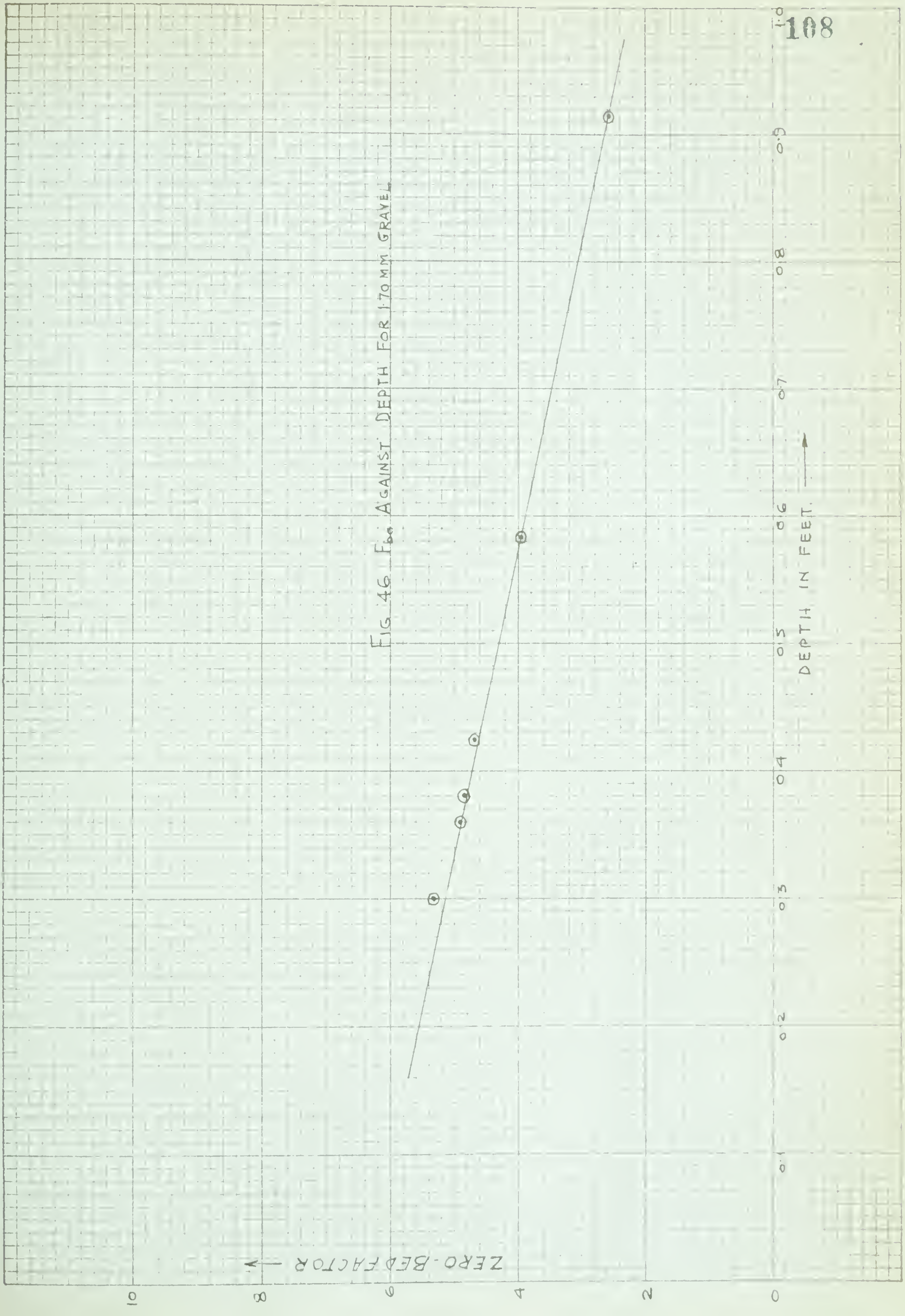

FIG 46 F_{bo} AGAINST DEPTH FOR 1.70 MM GRAVEL

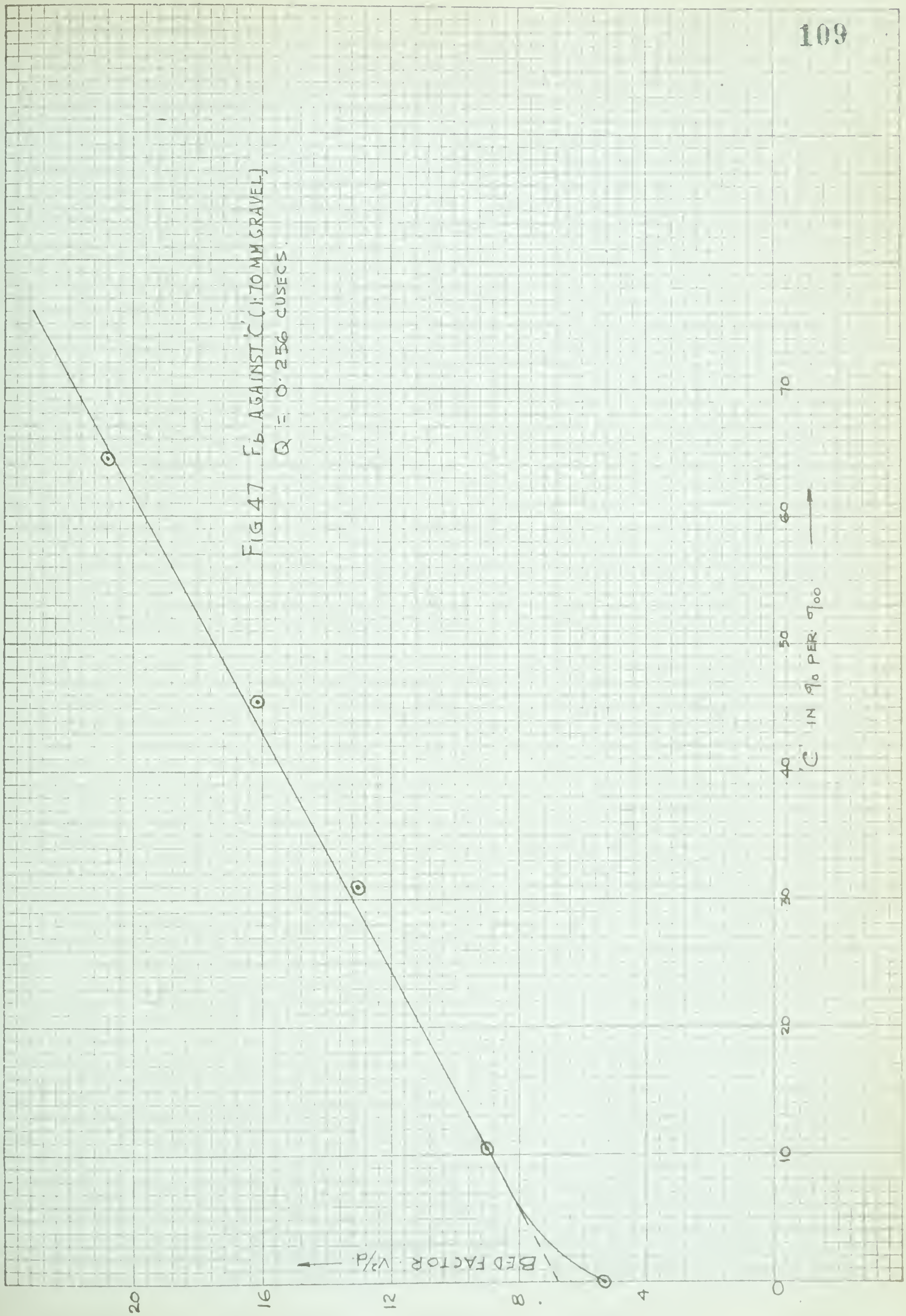

FIG 47 F_b AGAINST 'C' (1.70 MM GRAVEL)
Q = 0·256 CUSECS

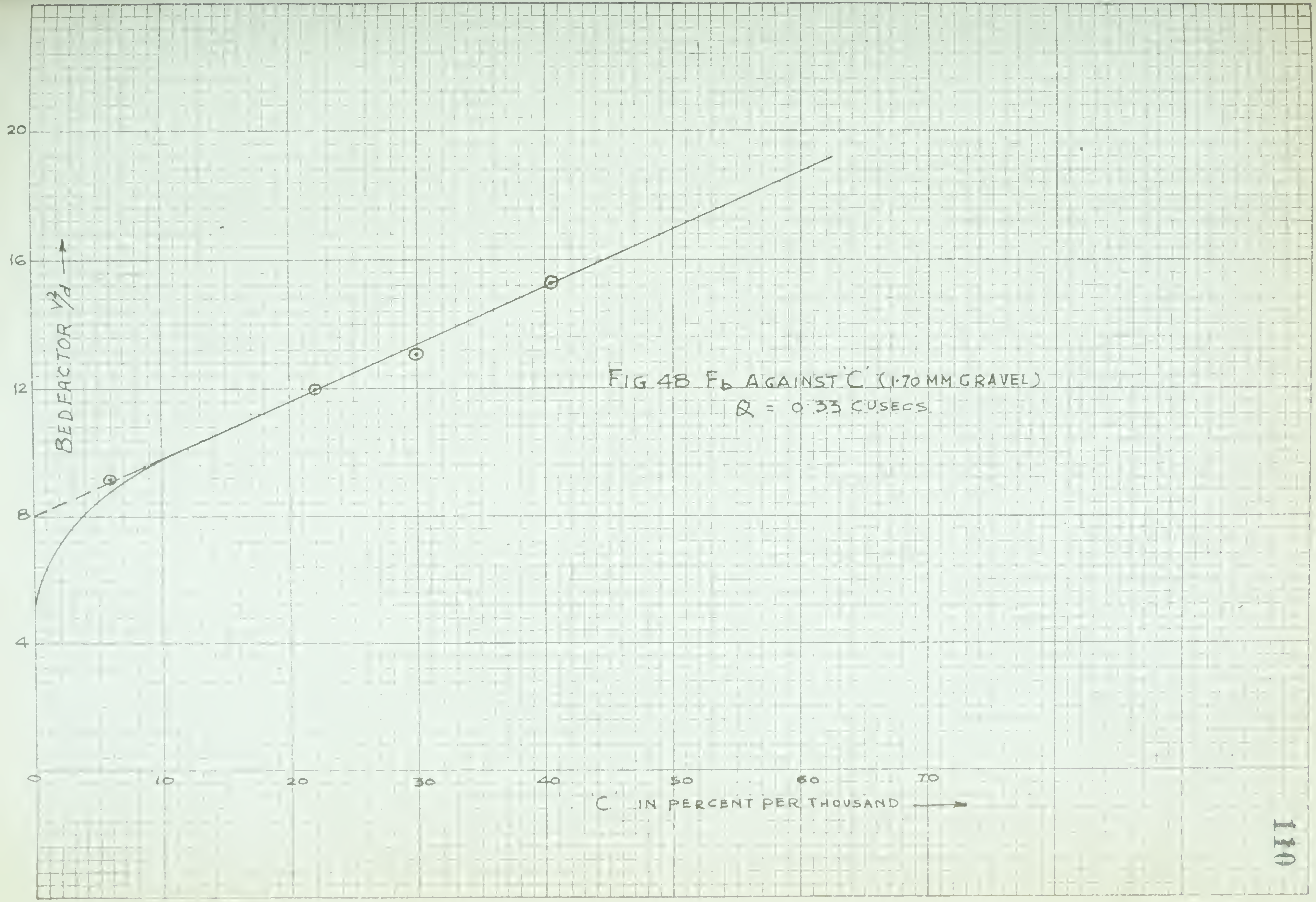

FIG 48 F_b AGAINST 'C' (1·70 MM GRAVEL)
Q = 0·33 CUSECS

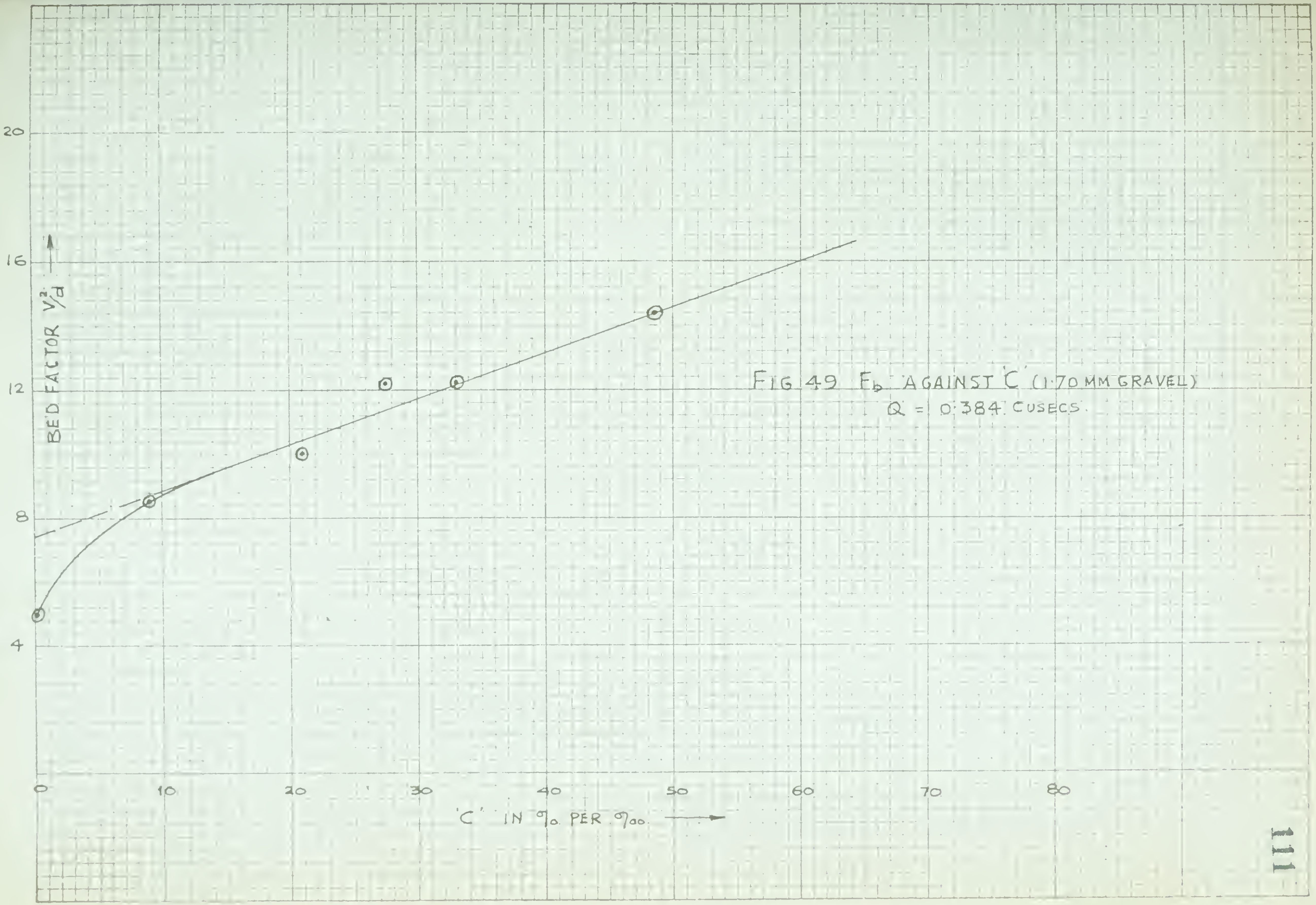

FIG 49 F_b AGAINST C' (1·70 MM GRAVEL)
$Q = 0{\cdot}384$ CUSECS

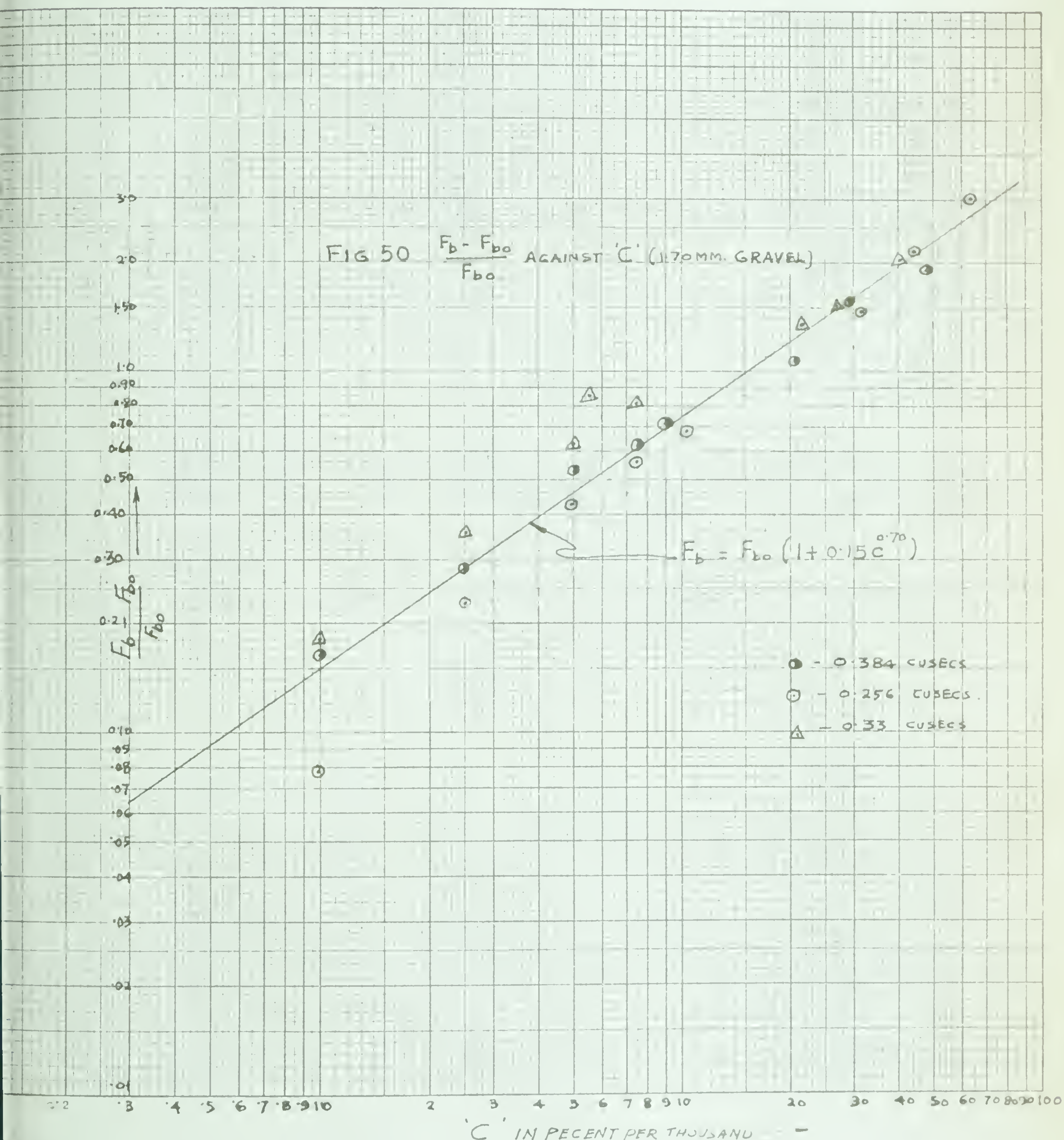

FIG 50 $\frac{F_b - F_{bo}}{F_{bo}}$ AGAINST 'C' (1.70MM. GRAVEL)
$F_b = F_{bo}(1 + 0.15C^{0.70})$
$\frac{F_b - F_{bo}}{F_{bo}}$
● - 0.384 CUSECS
⊙ - 0.256 CUSECS
△ - 0.33 CUSECS
'C' IN PECENT PER THOUSAND

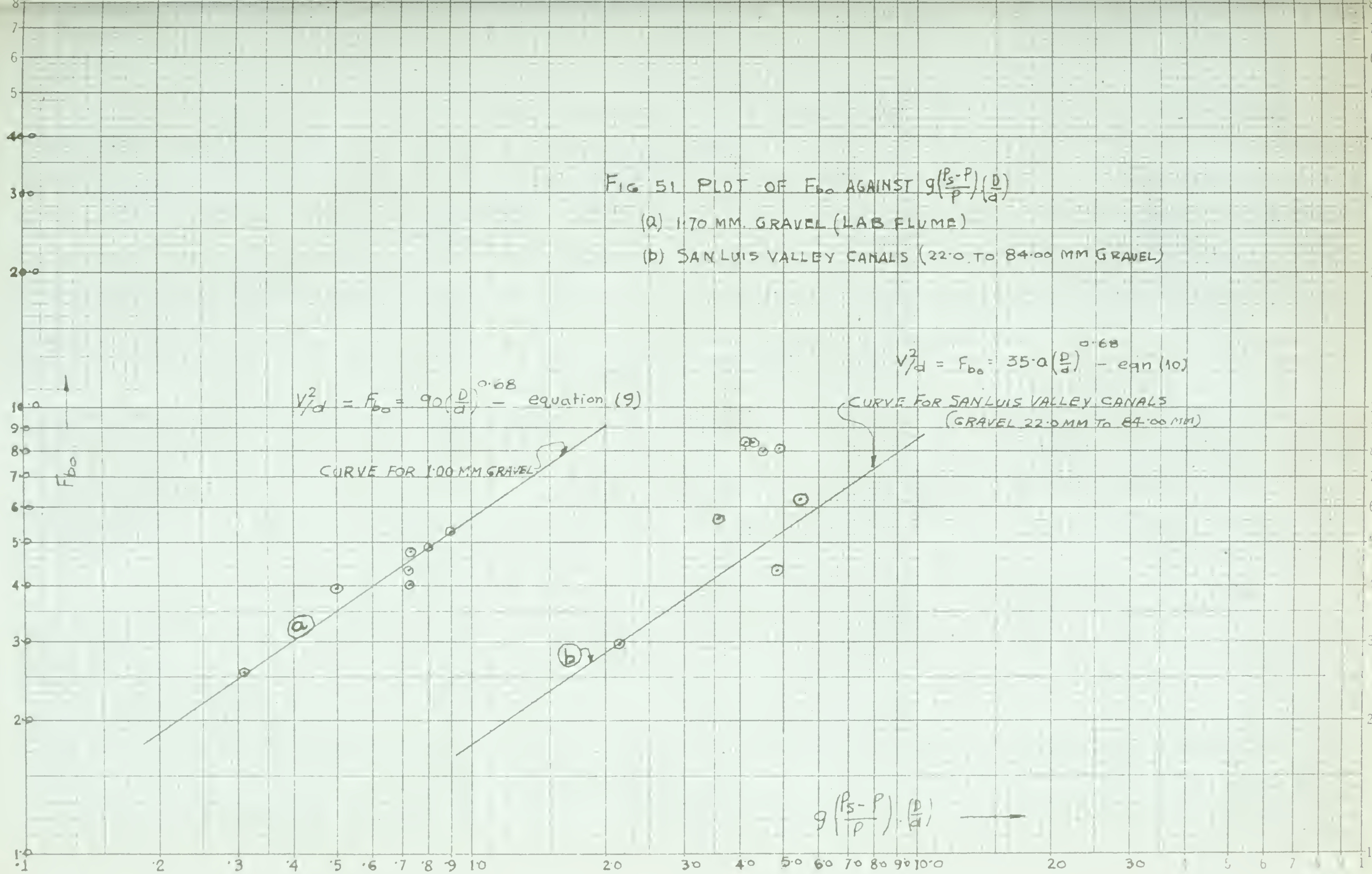

FIG 51 PLOT OF F_{bo} AGAINST $g\left(\frac{\rho_s-\rho}{\rho}\right)\left(\frac{D}{d}\right)$

(a) 1·70 MM. GRAVEL (LAB FLUME)

(b) SAN LUIS VALLEY CANALS (22·0 TO 84·00 MM GRAVEL)

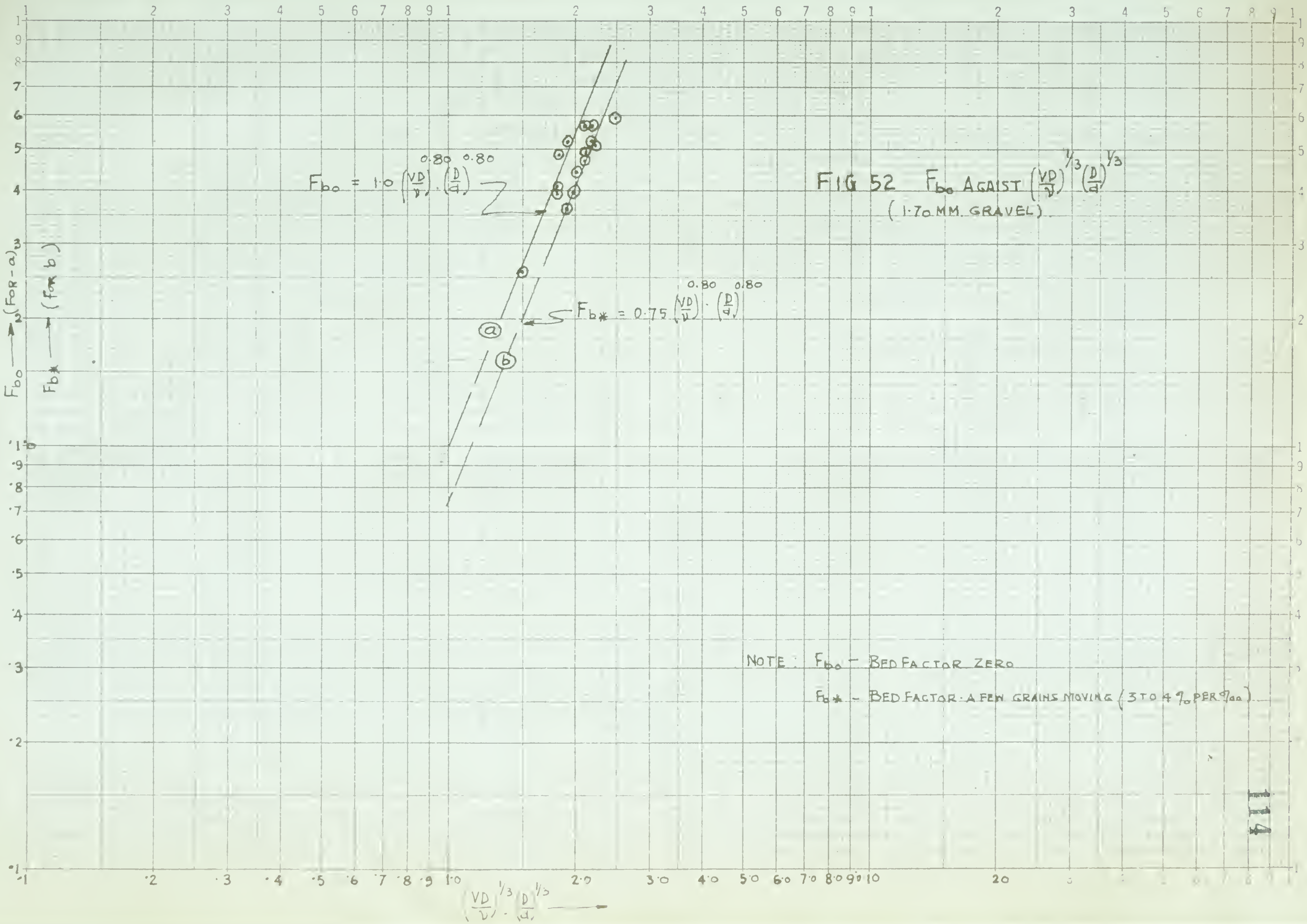

FIG 52 F_{bo} AGAIST $\left(\frac{VD}{\nu}\right)^{1/3}\left(\frac{D}{d}\right)^{1/3}$

(1·70 MM. GRAVEL)

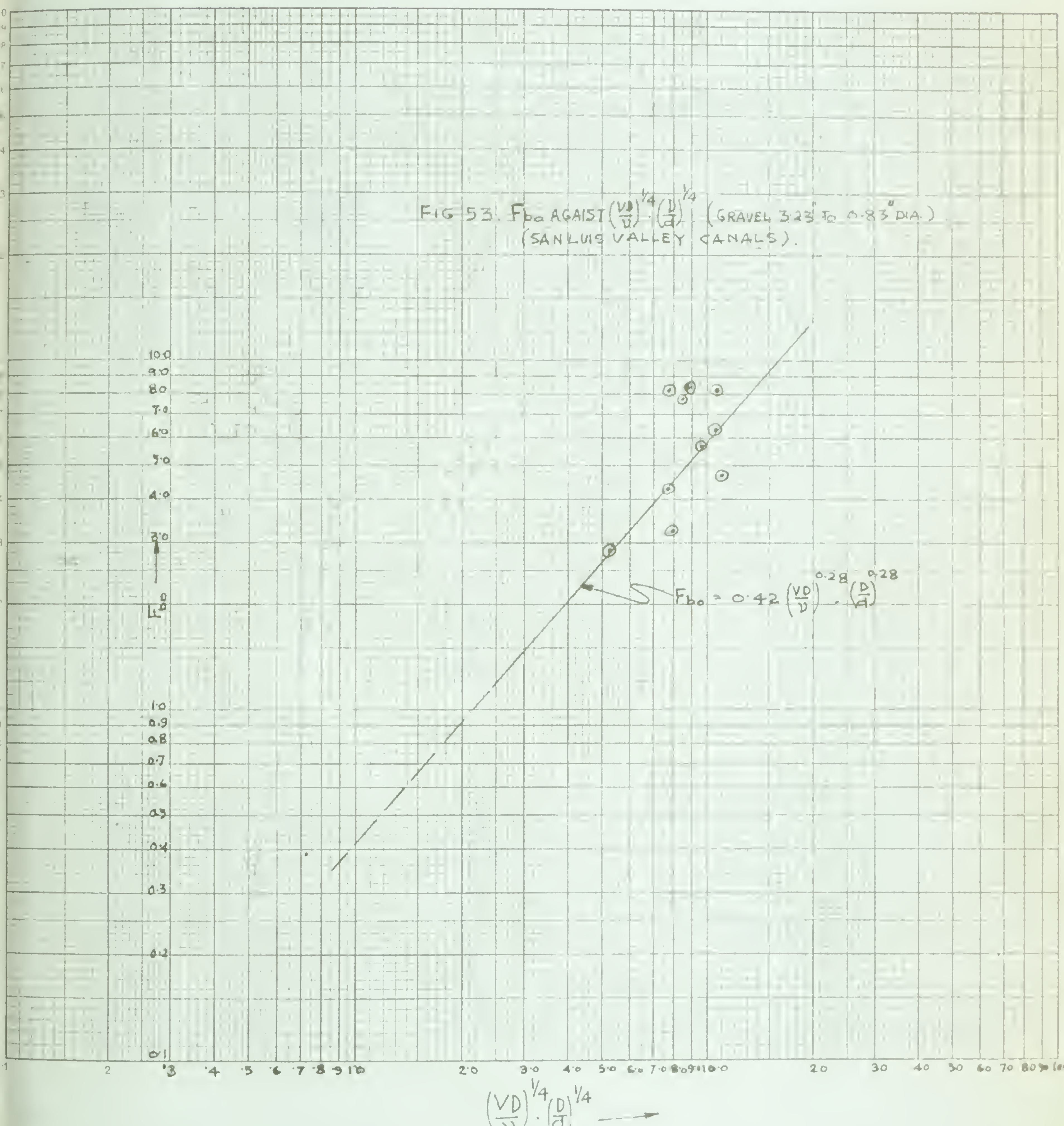
FIG 53. F_{bo} AGAIST $\left(\frac{VD}{\nu}\right)^{1/4} \cdot \left(\frac{D}{d}\right)^{1/4}$ (GRAVEL 3.23" TO 0.83" DIA.)
(SANLUIS VALLEY CANALS).
$F_{bo} = 0.42 \left(\frac{VD}{\nu}\right)^{0.28} \cdot \left(\frac{D}{d}\right)^{0.28}$
F_{bo}
$\left(\frac{VD}{\nu}\right)^{1/4} \cdot \left(\frac{D}{d}\right)^{1/4}$

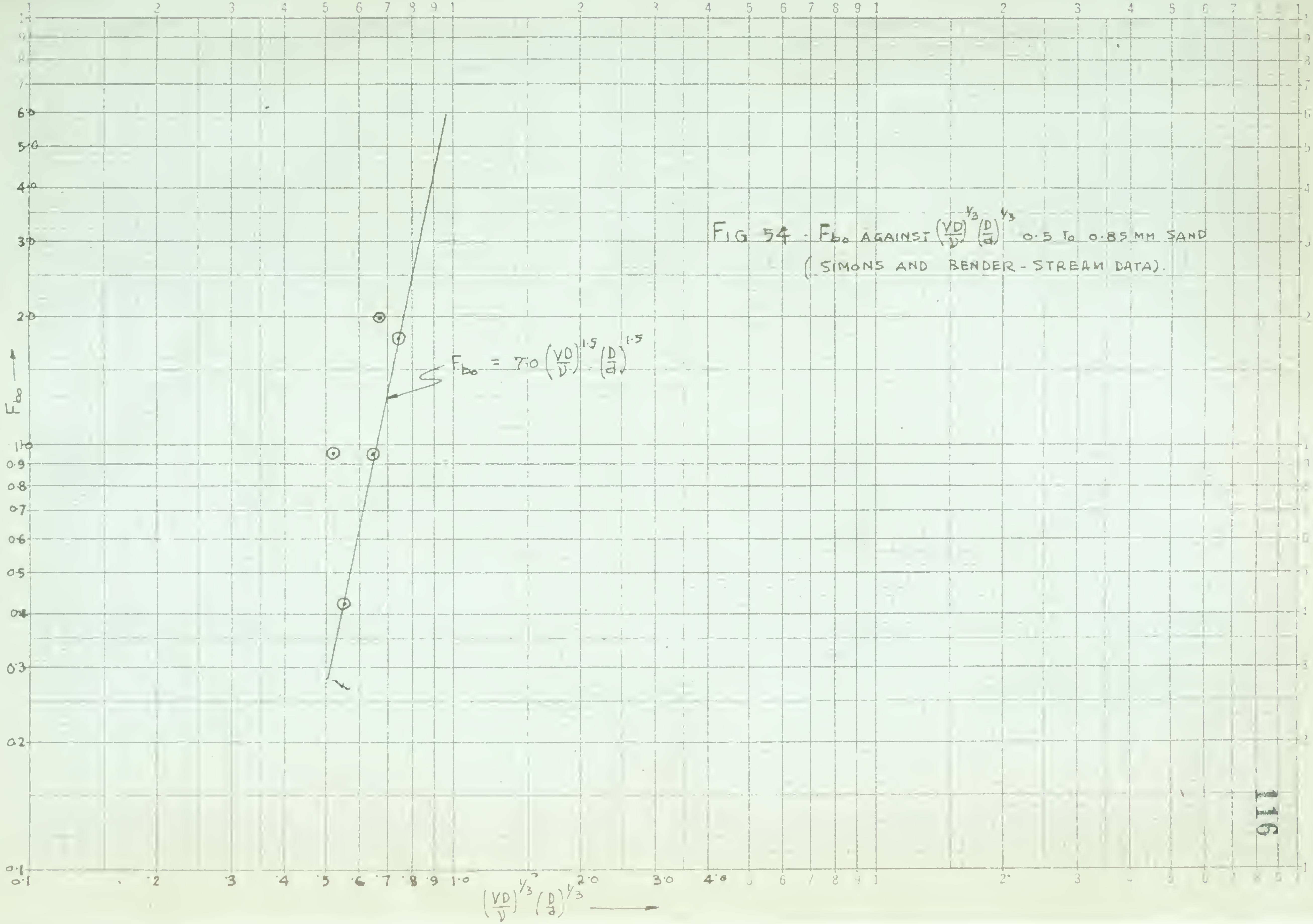

FIG 54. F_{bo} AGAINST $\left(\frac{VD}{\nu}\right)^{1/3}\left(\frac{D}{d}\right)^{1/3}$ 0·5 TO 0·85 MM SAND (SIMONS AND BENDER - STREAM DATA).